ACID PRECIPITATION IN ONTARIO STUDY

A METHODOLOGY FOR ESTIMATING THE IMPACTS OF ACID DEPOSITION IN ONTARIO AND THEIR ECONOMIC VALUE

PREPARED FOR

THE ONTARIO MINISTRY OF THE ENVIRONMENT

BY

VICTOR & BURRELL

in association with:

J.E. HANNA ASSOCIATES INC.

HATHAWAY CONSULTING SERVICES

UNITED TECHNOLOGY AND SCIENCE INC.

JUNE 1982

PREFACE

The models described in this report were based on data, information and dose-response relationships that were available through 1980.

Uncertainties inherent in the models were highlighted by the authors who identified numerous information gaps and who suggested a variety of ways in which the models could be improved.

Since that time, a great deal of additional research has been carried out in Canada and the United States concerning the effects of acidic deposition on forest, crops, aquatic ecosystems and building materials. Moreover, further data on the relevant resources at risk have been assembled.

Consequently, the Ministry has commissioned the DPA Group Inc. to review the models for the forestry, agriculture and "human systems" (e.g., materials) sectors and to suggest revisions and updates of relevant data. The DPA report will be completed by the winter of 1986 and the models will then be reprogrammed.

We hope to produce results from the revised models by the spring of 1987.

Corporate Policy and Planning
September 5, 1986

Victor & Burrell
Research and Consulting
72 Gothic Avenue
Toronto, Ontario
Canada M6P 2V9
(416) 763-3859

A Methodology for Estimating the Impacts of Acid Deposition in Ontario and their Economic Value

June 11, 1982

Submitted by:

VICTOR & BURRELL

in association with:

J.E. Hanna Associates Inc.

Hathaway Consulting Services

United Technology and Science Inc.

ABSTRACT

There are widely divergent views on the actual and potential effects of acid deposition. Unambiguous, measured impacts are scarce, and generally agreed dose-response relationships have yet to be established for effects on animal and plant species and on buildings and materials. An economic assessment of the present and possible future impacts of acid deposition over a land mass the size of Ontario is seriously confounded by this lack of knowledge on the nature and extent of the biophysical effects.

When properly validated relationships are unavailable one either says nothing about the likely extent of the impacts of acid deposition or makes assumptions based on whatever information is available. By funding this and related studies the Ontario Ministry of the Environment has chosen the latter course.

In approaching the task set for them the consultants have drawn upon information available in the international literature as well as on private communications with researchers in the area. A mutually consistent set of assumed relationships, that vary in their degree of empirical validation, have been assembled into a set of models. These models can be used to generate estimates of a wide range of impacts of acid deposition and their economic value. To do this for Ontario they must be used in conjunction with data specifically for the province on such factors as forested area, crop production, lake morphology, materials use and replacement. All the necessary data for using the

models have been assembled by the consultants and stored in the Ontario Government's Downsview computer. The models themselves have been programmed into the computer and may be readily accessed by staff of the Ontario Ministry of the Environment.

All of the models and data together comprise a computational framework which enables large amounts of data to be manipulated, and investigation of the implications for Ontario of alternative assumptions about acid deposition levels and dose-response relationships. Probablistic relationships have been incorporated to reflect the high degree of uncertainty in various assumptions in the models. If users of the computational framework so choose, these probabilities are carried through to any results obtained from the models so that the degree of uncertainty in the results can be made explicit.

As well as giving details of the models and data bases the report documents limitations of the models and data. These limitations should caution against placing too much confidence in the accuracy of any results obtained from the computational framework. They also provide important opportunities for improving the models and data bases. Accordingly, the report includes a number of recommendations for further work.

ACKNOWLEDGEMENTS

The consultants would like to thank the following people for their assistance in conducting the study:

G. Driver (OMAF)

H. Henry (OMAF)

G. Lentz (OMAF)

D. Fayle (MNR)

K. Armson (MNR)

S. Linzon (MOE)

B. Gizyn (MOE)

M. Griffith (MOE)

J. Donnan (MOE)

E. Dahl (Norway)

A. Henriksen (Norway)

Staff of the Crop Science Department at the University of Guelph

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION AND SUMMARY

1.1 THE PROBLEM

"The phenomenon of acid precipitation, commonly known as acid rain, is acknowledged by scientists and governments to be one of the most pressing environmental issues facing widespread areas of North America, western Europe and Scandinavia." (Ontario Ministry of the Environment, October, 1980).

It is the emission of sulphur dioxide (SO_2) and nitrogen oxides (NO_x) which, after a series of chemical reactions, give rise to acid deposition. The major anthropogenic sources of SO_2 are non-ferrous smelters, fossil-fired electricity generation stations, and other industrial operations. Volcanic emissions are the major natural source of sulphur. NO_x comes primarily from fossil-fired electricity generation stations, transportation and other combustion units.

Acid deposition, which includes both wet and dry deposition of mineral acids, may have a wide range of impacts. These include effects on:

a) Aquatic Systems such as reduced pH of water, increased solubility of toxic heavy metals, reduction in numbers and extinction of fish, amphibian and invertebrate populations, reduction in the diversity and production of some plant species;

b) Terrestrial Systems such as reduced pH of soil, accelerated leaching of some soil constituents (e.g., calcium, magnesium, phosphorus) increased supply of nitrate and sulphate, increased availability of toxic heavy metals, altered soil microbial activity and rate of litter decay, and changes in plant growth and some wildlife populations;

c) Man-made Systems such as increased deterioration rates of metals, paint, mortar and stone (including that used in many historical buildings and artifacts), discolouration and soiling of exterior finishes, and acidification of water supply systems;

d) Human Health such as damage to skin and hair and increased exposure to heavy metals through foodstuffs and water.

The relationships between the emission and deposition of contaminants causing acidification and direct and indirect effects on the chemistry of the physical environment and biological systems are poorly understood. This lack of precise cause and effect information is common to all components of the process both individually and in aggregate. Factors that may vary over time and space include rates of emissions, transportation mechanisms, climatological influences, soil and water chemical composition and reactions, biological processes and interactions with other contaminants. These factors give rise to a complex problem

and one to which it is not easy for governments to respond.

The situation is exacerbated by the fact that a significant portion of the SO_2 and NO_x emissions are transported a considerable distance from their points of discharge. With prevailing southwesterly winds, Ontario is a net importer of SO_2 and NO_x from the U.S. Moreover, some of Ontario's emissions of these gases are exported to Quebec and the Maritime provinces. The precise quantities of all of these inter-jurisdictional transfers of SO_2 and NO_x are unknown and are still under investigation.

In an attempt to gain a fuller understanding of the seriousness of the actual and potential impacts of acid deposition in Ontario, the Ontario Ministry of the Environment has funded three studies, of which this is one, on the socio-economic effects of acid deposition (Ontario Ministry of the Environment, July 15, 1980). One study addresses amenities aesthetic values affected and another considers the implications of acid deposition for tourism and outdoor recreation. Both of these studies are directed at damages for which actual market prices do not exist, but may possibly be estimated.

This study addresses a third and complementary category of effects that may be due to acid deposition: impacts on biological systems and human artifacts for which there are explicit market values. These include possible reductions or increases in the market value of agricultural, forest, commercial fur and fish harvests because of acid deposition. Increases or reductions in harvesting costs that may be caused are also

included as is the deterioration of materials embodied in buildings and structures and any additional maintenance or preventative measures that may be required.

1.2 STUDY OBJECTIVES

Originally, the study had two major objectives:

1. To develop quantitative estimates of the positive and negative effects that might be caused by acid deposition on goods and services for which market prices are available;

2. To estimate the economic value of these effects.

A further related objective was:

3. To identify the social implications of any of these effects and to comment on their significance.

In attempting to meet these objectives the consultants concluded that the dearth of information on the biophysical impacts of acid deposition seriously confounded any attempts to assess their economic value. Furthermore, the consultants found that there is a serious lack of useful biophysical information, particularly on dose-reponse relationships. Specific information gaps are highlighted in the recommendations. Furthermore, it would appear that much of the ongoing research effort

into acid deposition is highly specific in nature, and is therefore unlikely to be directly applicable to the assessment of provincial or regional impacts.

Faced with a lack of estimates of biophysical impacts to use as a basis for calculating economic values, and a paucity of scientific knowledge on which to make such estimates, the focus of the study was altered. In particular, far more emphasis than initially planned was placed on the methodological aspects of the problem so as to provide the Ministry of the Environment with a sound basis for future work and to assist the Ministry in determining its research priorities. As a result, rather than produce the estimates referred to in objectives 1 and 2 above and comment on their social implications (objective 3), the major contribution of the study is the development of a preliminary, yet comprehensive, methodology for generating estimates of acid deposition impacts in Ontario and their economic value. The primary objective of the methodology is to bring together, within a readily usable 'computational framework' the major scientific findings and other relevant information for estimating actual and potential province-wide impacts of acid deposition and their economic value.

1.3 APPROACH

1.3.1 Criteria

Several criteria were established for developing a suitable methodology:

i) <u>Theoretical Soundness</u>

Ideally, the methodology would incorporate well established causal relationships between acid deposition and those variables having economic value (eg. agricultural yields and materials deterioration). In the absence of such relationships, analyses developed for other purposes might be adapted to the task in question. For example, a calibrated set of relationships between soil acidity and forest productivity could be combined with a relationship between acid deposition and soil acidity. Unfortunately, in most instances neither of these approaches is possible. A third approach, and the one used most extensively in this study, is to hypothesize reasonable relationships between acid deposition and ecosystem productivity (materials deterioration in the case of buildings and structures). Available empirically determined relationships should support the hypotheses as far as possible and such relationships as are used should be consistent with generally acceptable biophysical theory and findings.

ii) Disaggregation by Region

Provincial estimates of impacts should be derived from estimates of impacts on ecologically distinct regions.

iii) Disaggregation by Receptor Category

Not only must forests, agriculture and fisheries be distinguished for impact analysis but individual species should be considered separately to allow for differential impacts across species.

iv) Time Horizon

A period of at least 20 years should be considered since actions taken to reduce emissions that cause acid deposition should be judged against the expectation of reduced impacts well into the future. The cumulative nature of some these impacts makes this consideration especially important.

v) Anthropogenic Deposition

The effects of anthropogenic sources of acid deposition should be distinguished from natural sources since control can only be exercised over the former.

vi) Sensitivity Analysis

The uncertainty inherent in all phases of assessing the impacts of acid deposition should be addressed explicitly through some form of sensitivity analysis which relates changes in impact

estimation to variations in key assumptions.

vii) Realistic Data Requirements

Full use should be made of the available data. Where a need for additional and improved information is indicated the data requirements should not be so demanding that the methodology cannot be implemented in the near term.

1.3.2 Overview of Methodology

It was decided early on in approaching this project that a methodology that could satisfy these criteria would have to consist of a set of models, one for each major receptor category (forestry, agriculture, etc.) that could be easily manipulated to perform the many calculations required and to cope with a considerable amount of data. Much of the work undertaken by the consultants went into the development of these models.

The models have been used as building blocks for a 'computational framework'. The computational framework allows the user to select the model or models to be run, and to select values for key assumptions to test their significance in terms of how they affect the predicted impacts of acid deposition and their economic value.

The following chapters describe in detail the individual models that have been developed in the course of this study and give the consultants' best estimates for each functional relationship contained in the models. The

computational framework, which allows the models to be used selectively and to test alternative assumptions, is also described. It is the computational framework, which has been programmed on the Government's computer and for which a comprehensive data set has been compiled, that forms the principal output of this project.

Throughout the discussion of the models that forms much of the body of this report, attention is drawn to their many limitations. These should be considered both as reasons for treating with caution any results obtained from their application, and as opportunities for refining the models so as to obtain more reliable results. One major omission in the models and accompanying data base is the exclusion of dry deposition because of a lack of data or estimates on dry deposition rates across Ontario (see Appendix A). Hence, throughout this report, in all discussions of the models, though not the general discussions of impacts, acid deposition refers only to wet deposition of mineral acids (i.e. in the form of rain or snow).

1.3.3 An Outline of the Models

Figure 1.1 shows the principal linkages between the exogenously determined acid deposition scenarios, their impacts on the yield of affected biological systems and the economic value of these changes. The impacts of acid deposition, modified by mitigation measures if any, on the yield of various receptors are estimated with a biological model. Impacts on yield may change harvesting costs and revenues from what they

FIGURE 1.1

Analytical Framework: Biological Systems

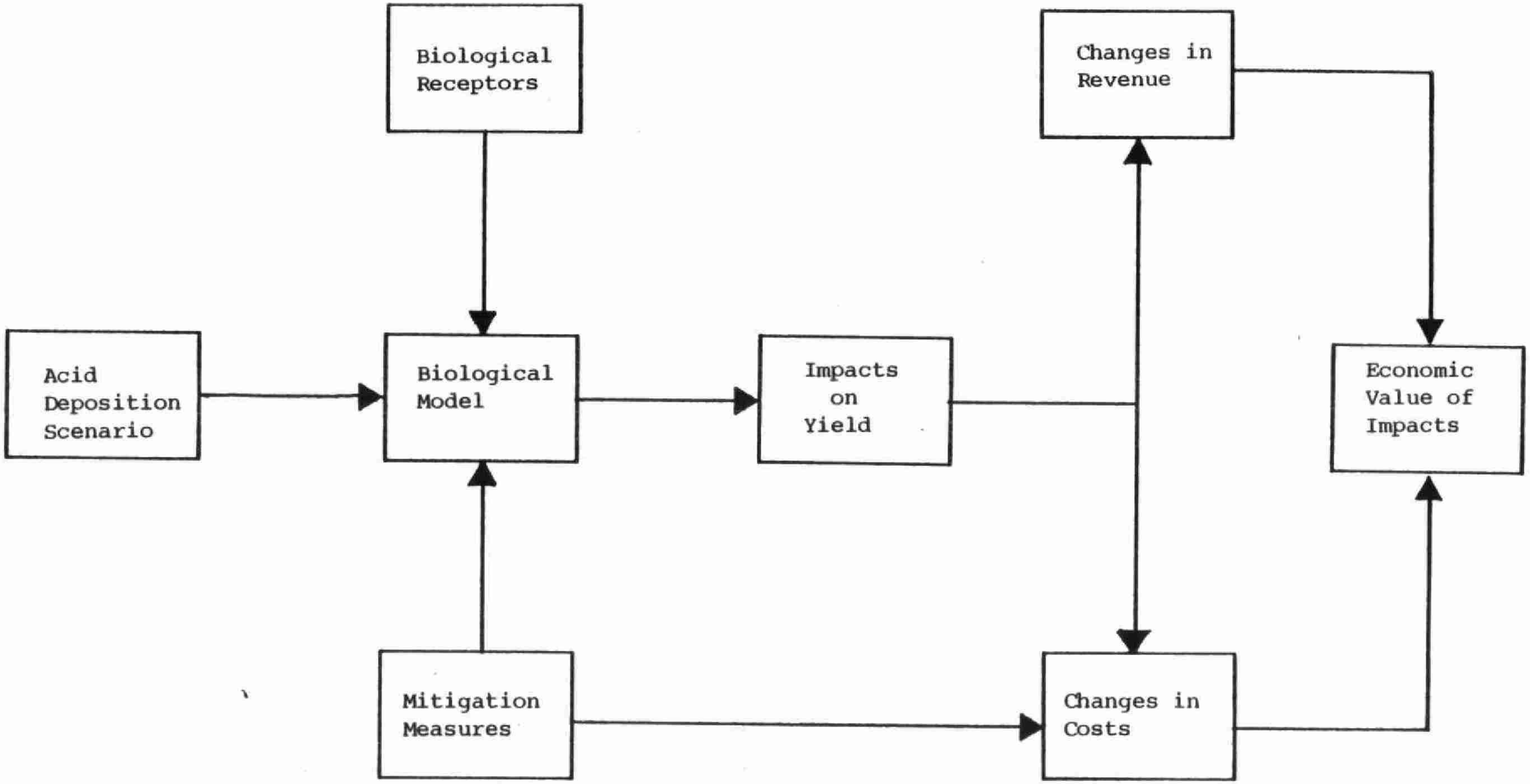
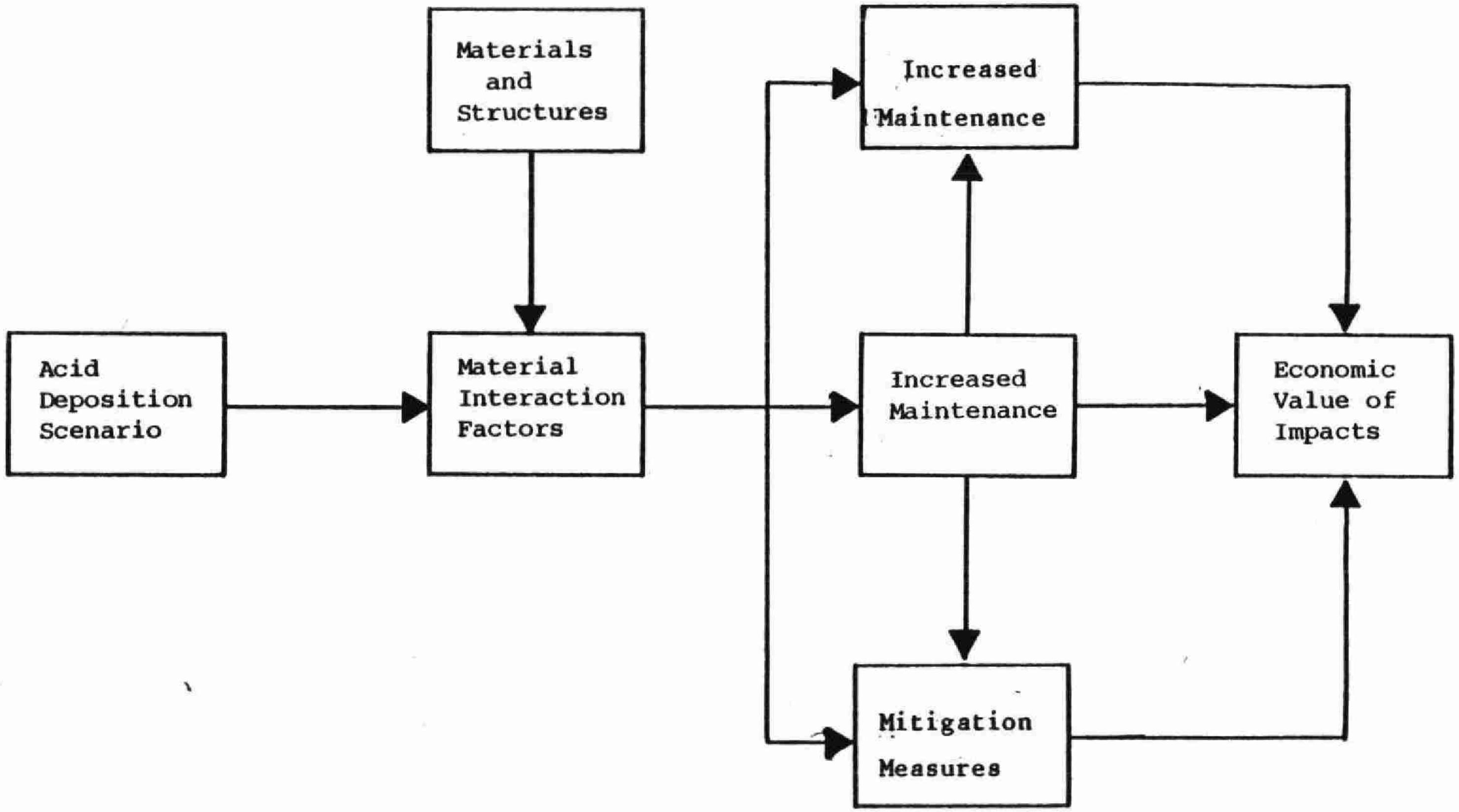


FIGURE 1.2

Analytical Framework: Buildings and Materials



would otherwise have been. Mitigation measures will also involve some increase in costs. The economic value of the acid deposition impacts is given by the addition of the changes in revenue and the changes in costs. For example, if revenues decrease by $X and costs increase by $Y, the economic cost of the impacts is $X + $Y. Beneficial impacts of acid deposition will show up as increases in sales revenue and/or decreases in harvesting costs. (The computational framework records all adverse impacts as positive dollar values and all beneficial impacts as negative dollar values).

In recognition of the changing impact of acid deposition over time, because of cumulative effects and varying acid loads, the models are designed to analyse potential impacts over a 22 year period. To allow for variations among geographical regions in the province, 64 ecologically distinct sub-regions are recognized. This multi-regional approach makes it possible to identify those parts of Ontario in which the impacts of acid deposition will be concentrated and hence, where the social implications are likely to be most pronounced.

Figure 1.2 shows the analytical framework used for estimating and valuing the impacts of acid deposition on materials and structures. The impacts of acid deposition are estimated with interaction factors derived from other studies. Depending on the material in question, acid deposition may give rise to increased maintenance and/or increased rates of replacement. Mitigation measures may be undertaken to reduce these impacts. It is the costs of all of these responses to acid deposition

for each of 64 regions in Ontario that can be estimated with the model for a period of 22 years.

1.3.4 Uncertainty and the Impacts of Acid Deposition

Possibly the one factor which overrides all others in assessing the economic damages (and benefits) of acid deposition is the high degree of uncertainty about the relationships between deposition and impacts. This uncertainty applies to impacts on biological systems and on buildings and structures. It reflects the inherent difficulty in identifying, measuring and predicting causal relationships when the range of potential impacts is so large, when so many factors have to be accounted for and when the area that is or might be affected is so extensive.

Uncertainty about various causal relationships assumed in the models is captured by representing these relationships as probability functions. The specification of these functions reflects the uncertainty of the user (or default values entered by the consultants) regarding the true relationships among the factors involved. While experimental results, where they exist, may influence the selection of the values of the functions, these values remain a representation of subjective uncertainty. <u>They should not be interpreted as statements of objective fact.</u>

The inclusion of probability functions directly in the biophysical models has two practical advantages. First, estimates of acid deposition

impacts and their economic value can be presented with their associated probabilities. It is hoped that this will avoid any misinterpretation of the damage (or benefit) estimates which might otherwise be assumed to be more definitive than present understanding and information allow. Secondly, the explicit inclusion of uncertainty in the form of probability functions also allows the uncertainty itself to become a focus for discussion. This may be very important for guiding new research initiatives.

In addition to the probablistic nature of key relationships incorporated in the models, the uncertainty that pervades the subject area necessitates the use of sensitivity analysis. Sensitivity analysis examines the implications for predicted impacts of changes in underlying assumptions. It draws attention to those assumptions which are most critical in terms of estimating the magnitude of the impacts and their economic value.

A major strength of the computational framework is that it allows the user to make changes in the assumptions easily. As described in greater detail in Chapter 2, each user of the computational framework, which is now operating on the provincial government's computer, can select values for a wide range of relationships used in the impact models (including values for the probability functions) and immediately generate a new set of impact estimates. In this way it is a simple matter to establish the sensitivity of the estimates and their economic value to changes in the assumptions. This is especially useful for determining the policy

relevance of disagreements about the assumptions and for identifying those issues most in need of further research. In other words, the computational framework provides more than a means for generating specific estimates of acid deposition impacts. It can be used to update estimates of acid deposition impacts and their economic value as new information becomes available. It can also be used to clarify and possibly resolve disputes about the impacts and their value among the various protagonists in the acid deposition debate.

The computational framework, its component models, and the data base assembled by the consultants, provide the Ontario Ministry of the Environment with a working analytical tool that should be of considerable use in guiding research activity on acid deposition and in assisting the Ministry in determining the best strategy for controlling emissions of sulphur dioxide and nitrogen oxides.

1.4 RECOMMENDATIONS

As the following chapters make clear there are many possibilities for continuing the work on estimating the impacts of acid deposition in Ontario and their economic value. These possibilities include specific items of scientific research leading to useful dose-response relationships as well as improvements in the data base so that a better use of existing information on impacts can be made. The following recommendations represent, in the consultants' view, the most important priorities for further work that will lead to better understanding of the magnitude and value of potential impacts of acid deposition in Ontario.

1.4.1 Recommendations Common to All Models

1. It is recommended that all appropriate modifications to the computational framework and data base be made and preliminary results be obtained from the computational framework using the Monte Carlo option. Although the models contain a high degree of uncertainty concerning certain relationships, in the study team's opinion they reflect the current level of knowledge and can provide a useful basis for making decisions on regulation and further research. The general perspective on province-wide impacts that can be obtained from the models complements the highly focussed, but often narrow, approach more commonly favoured by researchers in this area.

2. It is recommended that workshops or seminars for each model in the computational framework be convened and experts in the related fields be invited to attend. This would be a continuation of the peer review process already initiated. The resolution of several essential issues raised by reviewers will be facilitated through a direct exchange of view-points and information. A major objective of these workshops would be to provide better, although still subjective, estimates of the uncertainty associated with key relationships. This report and the online computational framework would provide a common starting base and there could be an immediate testing of proposed modifications.

3. It is recommended that the computational framework be linked with other models dealing with the physical and economic impacts of atmospheric pollutants, in particular precursors to acid deposition in order that an overall estimate of benefits and costs of pollutant emission reductions can be generated. When emission controls are enacted, the rate of acid deposition is reduced but in addition the direct effects of the emitted gases would be reduced. In this study, only the impacts of acid deposition have been considered. A rational emissions control policy needs to consider all aspects of emissions reduction.

4. It is recommended that the individual models be regularly updated as new research results become available. Extensive work on acid deposition impacts is underway in parts of Europe and North America. Undoubtedly, these efforts will lead to a better understanding of the phenomenon and will increase the reliability of damage estimates. Particular attention should be given to research efforts dealing with macroscale mass balance relationships similar to those used in this study. At this time, it appears unlikely that knowledge will advance over the short term sufficiently to permit the construction of much more detailed models of environmental systems for predicting acid deposition impacts on a wide scale.

5. It is recommended that the models be extended and modified as necessary to include the effects of dry deposition. This could enhance the relevance of the models considerably and, providing reasonable

estimates of dry deposition can be obtained, could be accomplished at a comparatively low cost.

1.4.2 Recommendations for Specific Models

FORESTRY

6. It is recommended that <u>the relationship between forest productivity and exchangeable calcium or other site parameters be investigated for forest stands in Ontario.</u> Some information from North America is available relating site index to soil chemistry parameters. This data base could be readily augmented by selected field surveys. The analysis should be conducted such that one or more parameters could be related interactively with acid deposition. As part of this survey, the estimates of input soils parameters for each region could be improved.

7. It is recommended that <u>the proportion of atmospherically deposited nitrogen which is uptaken by forest stands be determined to refine the estimates of stimulatory effects.</u> In the model, it is assumed that all nitrogen is available for forest uptake. However, the portion that falls and runs off during the non-growing period cannot be used by trees. Mass balance studies such as those available from various calibrated watersheds, (i.e., Dorset, Turkey Lake, ELA, etc.) will assist in this exercise.

8. It is recommended that the stimulatory effect of sulphur on tree growth be examined and included in the model if a net effect is observed. Fertilization experiments using sulphur have not been widely published in North America; this being the reason that no allowance is currently made in the model for sulphur.

9. It is recommended that the feasibility of using acid causing anions (i.e., $SO^{=}_{4}$ and NO^{-}_{3}) in the soil mass balance equation be investigated. Hydrogen ion is currently used to drive soil acidification in the model. However, the hydrogen cycle is highly complex and not well understood, which is partly a function of its ubiquity in the environment. For basic cations to be displaced in the soil mantle an accompanying anion must be present. Therefore, nearly a direct substitution in the model is possible between hydrogen and sulphates and nitrates in the soil mass balance equations. These ions are easier to trace through an ecosystem.

10. It is recommended that research be conducted to quantify the relationship between foliar injury and wood production and the results inserted in the forestry model. This is essential in estimating the economic value of damages. Field observations based on partially or totally defoliated stands, (i.e., SO_2 fumigation, forest tent caterpillars, etc.) could be used to develop approximate curves without undertaking extensive laboratory experiments.

11. It is recommended that <u>dose-response experiments be conducted for the major forest species in Ontario.</u> The dose-response curves generated by the consultants was based primarily on data from U.S. studies and a number of the principal species in Ontario have not been tested. These experiments should attempt to segregate effects according to stage of development, site and climatic conditions and the permanence of damage in the case of conifers.

12. It is recommended that <u>the relationship between wood costs and forest productivity be estimated through econometric studies in which other factors are held constant.</u> This will improve the accuracy of the relationship presently assumed in the model.

AGRICULTURE

13. It is recommended that <u>the basic input data be refined according to the 64 regions used.</u> Much of the input data on crop varieties, soil conditions, soil management practices and farming costs have been averaged across the province. However, the model is fully capable of accepting data for specific regions. This data compilation would require the co-operation of the Ontario Ministry of Agriculture and Food and could be expedited by dealing individually with local agricultural representatives.

14. It is recommended that <u>experimental conditions used to generate the data for the dose-response curves be carefully examined and the</u>

models corrected, if necessary, to avoid double counting of soil effects. As mentioned in the text, generally accepted experimental procedures for conducting dose-response studies have only recently been approved. The data used for the relationships in the model were generated under a variety of conditions without detailed corrections being made.

15. It is recommended that dose-response experiments be conducted for the major crop varieties in Ontario using soil and climatic conditions comparable to the regions where they are grown. These experiments can be performed and replicated over a relatively short time horizon and would greatly add to the confidence associated with the foliar response equations. Care should be taken in these experiments to differentiate foliar and soil impacts. Consideration should also be given to the effects on crops at various stages of development.

16. It is recommended that the proportion of the atmospherically deposited nitrogen and sulphur which directly substitutes applied fertilizers be refined by examining the seasonal deposition pattern and through input-output monitoring. In the current model, all nitrogen and sulphur is considered available for plants which likely overestimates the benefit. The proportion should include dry and wet deposition and should account for any chemical forms which are stable and not available for plant uptake.

17. It is recommended that the relationships between physical damages and economic value be modified to account for changes in market value. Currently, a direct relationship is assumed between reduction in yield and economic loss. However, for some crops, changes in the physical appearance of produce may be quite significant in determining market price. These relationships would need to be derived for each crop or group of crops.

COMMERCIAL FUR

18. It is recommended that impacts of acid deposition be predicted for each fur bearer species individually when the data become available. The approach of lumping all species in a region in terms of response is quite general and does not reflect the individual variations which can be expected between species. As part of this differentiation, species could be segregated according to terrestrial and aquatic habitats with the terrestrial species related to forest and edaphic impacts and aquatic species responding to changes in lake chemistry and productivity.

COMMERCIAL FISHERIES

19. It is recommended that a comprehensive approach to predicting the impact of short term reductions in lake alkalinity and pH on fisheries productivity and estimation be developed and integrated with the long-term acidification model. Short term acid pulses during periods of high runoff are suspected to have a direct mortality effect on adult

fish, fry and spawn, as well as having potential sublethal effects such as reduced fitness. These types of impacts comprise two biological responses, one being a varible recruitment/mortality phenomenon, and the other being an indirect effect on productivity and survival. To deal with this problem, a stochastic model for both the physical/chemical and biological components is required. The results of such an analysis would then need to be superimposed on the morphoedaphic index (MEI) predictions since fish stock depletion can lead to an overestimate of yield for a particular species by the MEI.

Additionally, lake alkalinity partially determines susceptibility to acid pulses, and by integrating the long-term acidification into the pulse model, it would be sensitive to long term changes. As part of this approach, the model would need to be partitioned into shorter type periods (monthly or daily intervals) to better predict ambient alkalinities in relation to the frequency of runoff and outflow, and primary production rates.

20. It is recommended that a more direct relationship be developed between lake alkalinity and fisheries production, perhaps through total phosphorus. There is considerable scientific evidence demonstrating the importance of total phosphorus to phytoplankton biomass and primary production in oligotrophic Precambrian Shield lakes. No relationships exist between a lake's alkalinity content and its fisheries production.

21. It is recommended that field investigations be undertaken to gain better estimates of soil depth (S), cation exchange capacity (CEC), and base saturation (BS). Approximate measurements for groundwater flow and alkalinity concentrations would also be useful. The Department of Fisheries and Oceans model which is used in this study, focussed on loss of sports fish on a regional basis. This model was modified for application on an individual lake basis to deal with 107 commercially fished inland lakes, (i.e. the lakes fished commercially in 1979). Measured data for each would provide better agreements between predicted and measured lake alkalinities, thus increasing confidence in the model on the part of scientists, managers and policy makers.

BUILDINGS AND STRUCTURES

22. It is recommended that values for the economic life of materials, exposure factors and thicknesses of materials in use be estimated specifically for Ontario. The use of data from the United States, much of which applies to conditions 15 years ago, could be improved by collecting data for Ontario.

23. It is recommended that estimates of Ontario's standing stock of buildings and materials in physical units be prepared. Such estimates could provide the basis for direct estimates of physical damages to buildings and materials from acid deposition and other pollutants, rather than to continue to rely on dollar value surrogates.

24. It is recommended that carefully selected case studies of the economic implications of corrosion of specific materials in place be undertaken. These studies are important for those materials the economic cost of which may be many times less than the economic value of damages caused by component failure.

25. It is recommended that research be undertaken into the specific impacts of acid deposition on buildings and structures, rather than rely on extrapolations from studies of general air pollution. Synergistic effects of acids with other pollutants should be included.

CHAPTER 2

THE COMPUTATIONAL FRAMEWORK

A computational framework was developed in this study for use in calculating the estimated biophysical effects of acid deposition and their economic value. The framework is designed to fulfill four objectives:

i) to process large amounts of data using assumptions consistent with the latest findings and views of scientists working on the effects of acid deposition;

ii) to incorporate expressions of uncertainty regarding key relationships between acid deposition and its effects;

iii) to enable the Ministry of the Environment to revise its estimates of effects and costs as new information becomes available;

iv) to provide the Ministry of the Environment with an analytical tool that generates policy relevant output:

- disaggregated receptor categories;
- sub-provincial regional estimates of impacts;
- time dependent results

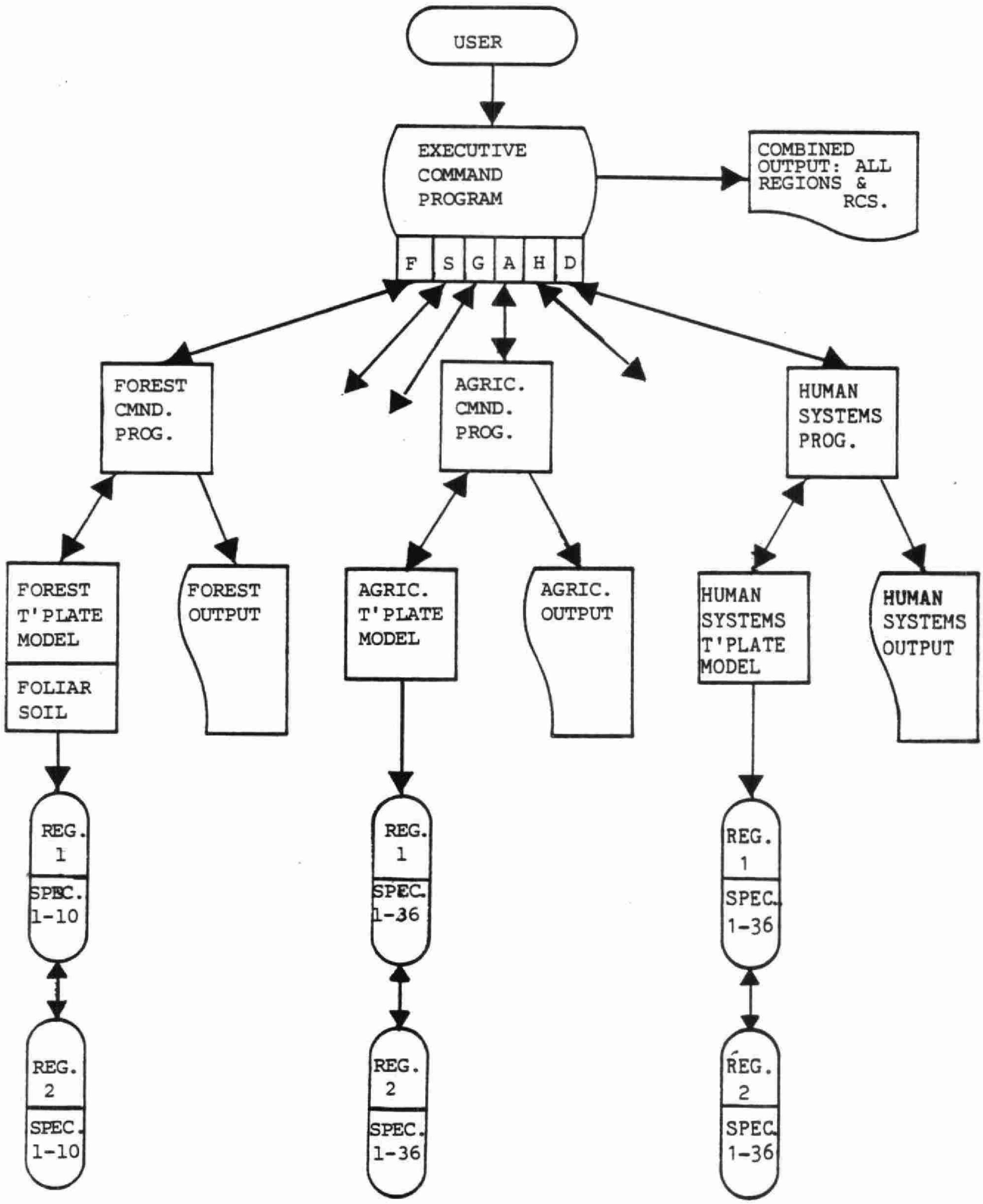
- damage estimates capable of presentation in terms of probable magnitudes .

Figure 2-1 shows a schematic outline of the computational framework. The executive command program gives the user access to several 'template' models, one each for forestry and commercial fur, agriculture, commercial fishing, and buildings and structures. Each of these template models can be run for any of the individual 64 sub-regions or groups of sub-regions by calling up the appropriate datafile. (In the case of fisheries, the template model is run for 107 individual lakes, each with its own datafile). The user has a wide variety of choices to make regarding assumptions about the rate of change in acid deposition over time, values for functions that relate deposition to impacts, and the discount rate to be used in the economic calculations. Appropriate 'prompts' are built into the computational framework. 'Monte Carlo' simulation, where values of parameters are drawn from a specified probability distribution, can be selected. (In Monte Carlo simulation the models are, in effect, rerun many times and each time new values are selected for those variables for which probability distributions are specified. The final results, which are reported on a probablistic basis, reflect the forms of the probability distributions incorporated in the models.) Finally, the user can choose to see, for any year, the values of any input variable, intermediate variable, or any output variable once a model has been solved.

This flexibility and ease of use is made possible by the choice of IFPS

Figure 2.1

Schematic Outline of the Computational Framework



(The Interactive Financial Planning System) as the modelling language. "A major contribution made by IFPS is that it provides a workable analytical and decision-oriented environment for open and understandable communication. IFPS provides the means for reducing or eliminating conflicts, intimidation by technical jargon, and personal goal setting when managers and technicians should be working together as a team." (IFPS Users Manual, 1980). It should be stressed that the comparative simplicity of IFPS allows users to make changes to the models quite easily, over and above those for which allowance has already been made through prompts and user selected values.

Output from the computational framework is provided to the user for each of five major regions in Ontario. Table 2-1 shows the correspondence between these regions and Hills' site regions and site districts. Table 2-2 shows the correspondence between Hills' site regions and site districts, and the sub-regions and lakes as numerically defined in the data files of the computational framework. (See figure 3.1 for a map of Hills' site regions and districts.) Output for each of the individual 64 regions or any grouping of them, or each lake or any group of lakes, can also be easily selected by the user.

To aid users of the computational framework, a glossary of terms has been included in Appendix D, together with all of the program code. The following chapters provide a detailed account of each of the models (i.e., template models in IFPS terms) that have been built for the Ministry and that can be used and modified to estimate acid deposition

impacts in Ontario, and their economic value.

TABLE 2-1

CORRESPONDENCE BETWEEN THE FIVE
MAJOR SUB-REGIONS AND HILLS' SITE REGIONS
AND SITE DISTRICTS

Major Sub-Regions	Hill's Site Region and Site District
Northwest	1E, 2W, 3S, 4S, 5S 3W, 4W
Northeast	2E, 3E, 4E, 5E.1-10
Southeastern	6E.10-12, 5E.11, 5E.12
Central	6E.6-9, 7E.3, 7E.4
Southwest	6E.1-5, 7E.1, 7E.2

TABLE 2-2

CORRESPONDENCE BETWEEN HILLS' SITE REGION AND SITE DISTRICTS AND SUB-REGIONS AND LAKES DEFINED IN THE COMPUTATIONAL FRAMEWORK

Hill's Site Regions and Site Districts		Sub-Regions	Commercially Fished Lakes (Potentially Susceptible to Acid Deposition)[1]
Lakes Erie-Ontario			
7E.	1	1	
	2	2	
	3	3	
	4	4	
Lakes Simcoe-Rideau			
6E.	1	5	
	2	6	
	3	7	
	4	8	
	5	9	
	6	10	
	7	11	
	8	12	
	9	13	
	10	14	
	11	15	
	12	16	
Georgian Bay			
5E.	1	17	
	2	18	
	3	19	
	4	20	4
	5	21	5
	6	22	
	7	23	
	8	24	
	9	25	
	10	26	
	11	27	
	12	28	
Lake of the Woods			
5S.	1	29	48*-50, 56*-59, 62-65
	2	30	
Lake Wabigoon			
4S.	1	31	90, 94
	2	32	75, 79, 88, 89, 91
	3	33	67, 69-71, 84
	4	34	82, 83, 85, 87, 92, 93
	5	35	51, 60, 61, 86
Pigeon River			
4W.	1	36	52-55
	2	37	1

TABLE 2-2 continued

Lake Temagami			
4E.	1	38	
	2	39	
	3	40	46, 47
	4	41	
	5	42	
Lake St. Joseph			
3S.	1	43	10, 11, 14, 29-34, 76-78, 80, 81, 95-106
Lake Nipigon			
3W.	1	44	35-37, 39, 42, 43, 45
	2	45	68, 72-74
	3	46	2, 3
	4	47	40, 41, 44
	5	48	
Lake Abitibi			
3E.	1	49	
	2	50	
	3	51	
	4	52	
	5	53	45
	6	54	
Big Trout Lake			
2W.	1	55	6-9, 19, 18
	2	56	
	3	57	12, 13, 15-17, 20-26, 28, 38
James Bay			
2E.	1	58	
	2	59	
	3	60	
Hudson Bay			
1E.	1	61	
	2	62	
	3	63	
	4	64	

[1]The names of the lakes are given in Appendix B

*These lakes overlap the boundaries of two or more sub-regions. They were assigned to the sub-region in which their major portion lies.

Chapter 3

FORESTRY

CHAPTER SUMMARY

This chapter begins with a review of the effects of acid deposition on forest productivity. Soil effects and foliar effects are considered separately. Despite a considerable literature, detailed relationships between acid deposition and impacts on forest yields have not been well established.

The soils response model and foliar response model that are described in the chapter and the values given for the various parameters, provide a basis for estimating acid deposition impacts on forest productivity in Ontario using available information. These models, together with an economic component that relates forest productivity to wood costs, may be accessed through the computational framework.

3.1 INTRODUCTION

A multiplicity of natural factors influences forest productivity. Some of the major ones are:

- climate;
- edaphic (soil) parameters: texture, depth, available moisture and chemical composition;
- genetic characteristics of local strains;
- stand age;
- stocking and tree density;
- insects;

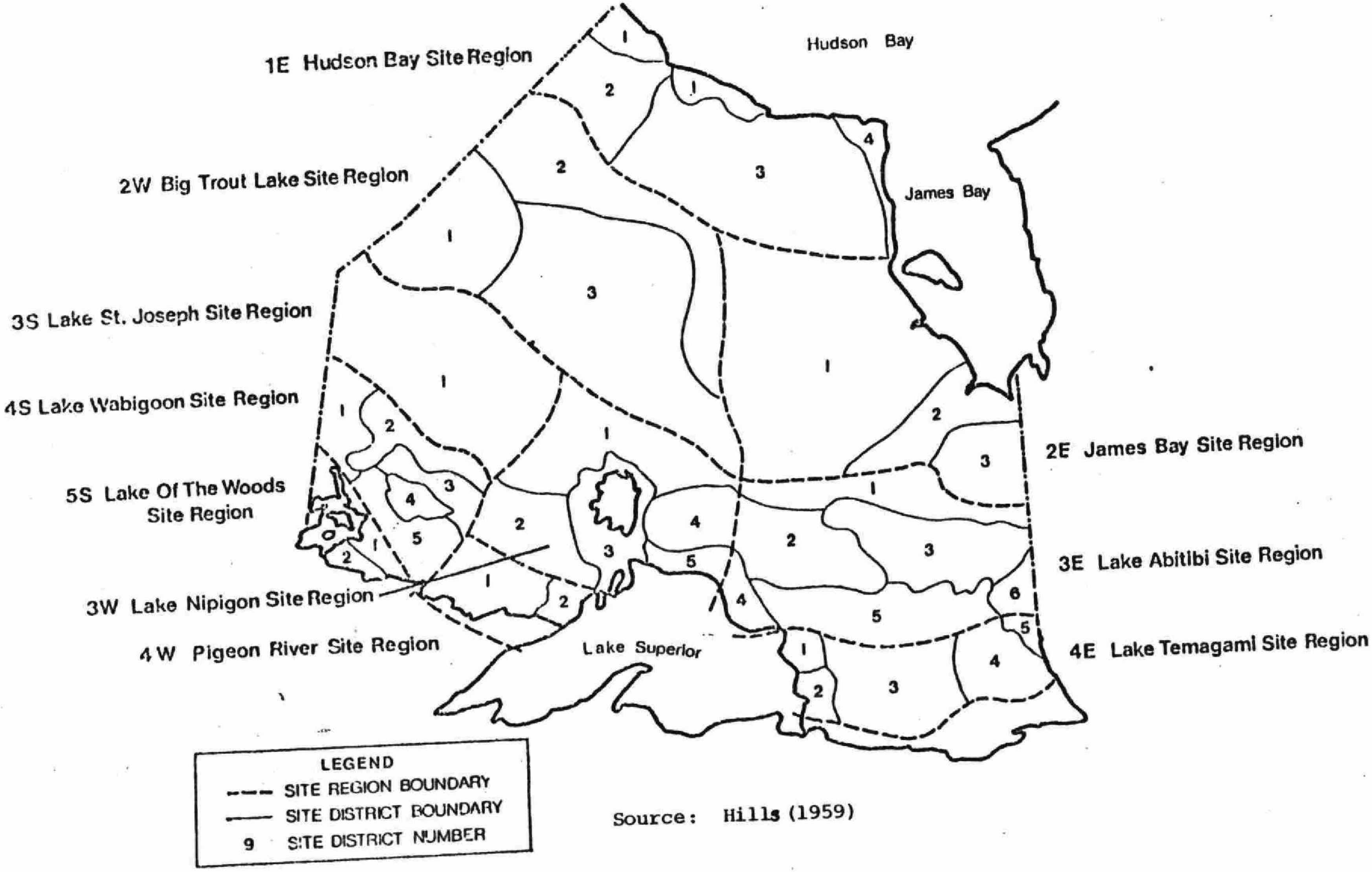
- disease;
- fire.

Since each of these may and does vary independently, both spatially (among sites), and temporally (among years), the productivity of forest ecosystems is highly variable. However, forest managers do predict wood production by examining large scale features, such as climate and physiography, and through detailed examinations of forest stands using air photo interpretation and field sampling. While these predictions have an error factor relating to natural annual variations and unpredictable catastrophies (e.g., fire, disease, windstorms, etc.), they are used as the basis of management decisions regarding harvesting and regeneration practices.

Some of the first work in Ontario and Canada to systematize the prediction of forest productivity was undertaken by Hills (1959). He subdivided the province of Ontario into major site regions, primarily on the basis of climate and physiographic conditions. Each site region was subsequently subdivided into site districts, on the basis of vegetation and landform (see figure 3-1). He also developed a system to describe forest stands within a site district according to microclimate, moisture regime, and soil characteristics. His scheme is used in Ontario, and the Ontario Land Inventory and Canada Land Inventory are based on many of the concepts advanced by Hills. Forest resource inventories have also been prepared for most of the merchantable stands of timber in the province, to assess current standing volumes and annual increments or productivity.

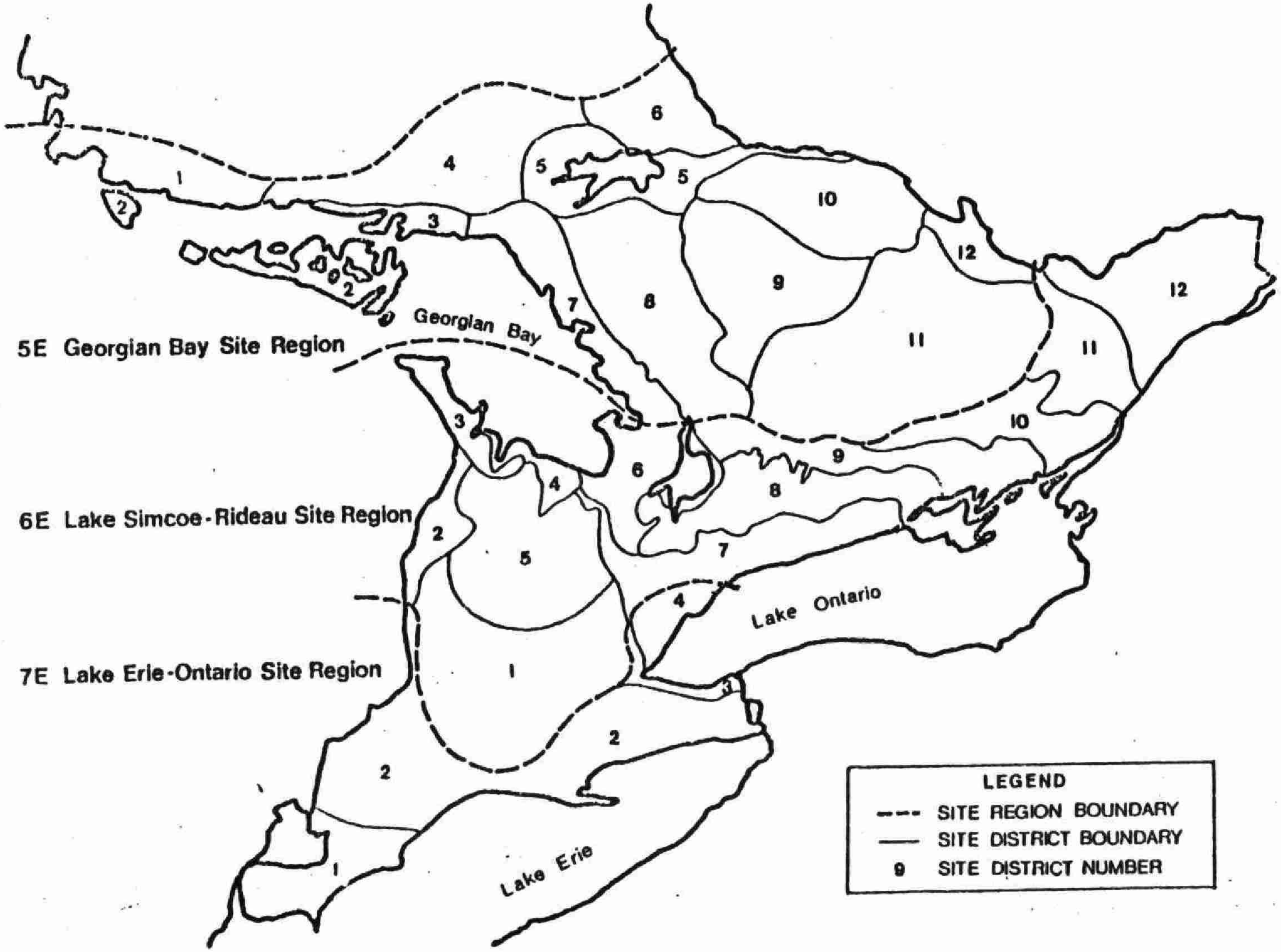
Figure 3.1

Hills' Site Districts and Regions



Source: Hills (1959)

Figure 3.1 (cont.)



Source: Hills(1959)

Estimates of annual increment or productivity are based on measurments of selected trees in a forest stand in terms of age, height and trunk size and comparing these values to standard yield tables (Plonski, 1974). This method provides a net response of the forest to its environment. Accordingly, forest managers have a fairly good macroscale understanding of natural forest productivity and current standing volumes, though the precise role of each specific factor affecting productivity is not yet fully understood.

Forest productivity may be affected by acid deposition through two primary although not necessarily independent mechanisms, specifically, foliar effects and soil effects. The former are caused by impingement of acidic substances on the foliar surfaces (i.e., needles and leaves). Soil effects occur when the acid reaches the ground and changes the physiochemical environment, leading to alterations either in microbiological processes or in the chemical environment of the tree roots.

The lack of detailed knowledge about how variations in soil or foliar characteristics affect productivity poses a considerable problem for predicting the impacts of acid deposition on forest yield. Until such information is available it is necessary to rely on a basic understanding of forest ecosystems and on empirically observed relationships between acid deposition and other factors believed to be important for forest yields, without articulating all of the causal connections involved.

3.2 FOREST PRODUCTIVITY AND THE EFFECTS OF ACID DEPOSITION: BACKGROUND

3.2.1 Soil Effects of Acid Deposition

A number of soil effects of acid deposition have been noted in the literature:

These include:

- increased leaching of nutrients and elements such as calcium, magnesium, potassium, and sodium from the active soil layers;
- reduced microbiological nitrogen fixation;
- reduced rate of decomposition of soil organic matter;
- increased mobilization of aluminum and manganese;
- reduced soil pH and base saturation;
- increased concentrations of sulphur and nitrogen compounds.

These effects could influence forest productivity, both positively and negatively. For example, Aber et al. (1981)have taken a forest ecosystem productivity model developed by Botkin et al. (1972), and included a subroutine in which acid deposition reduces the decomposition of organic matter, and hence causes a reduction in the rate of nitrogen cycling, which in turn leads to reduced productivity. Researchers in the Solling

Plateau of West Germany have been examining the influence of aluminum mobilization on root function since 1966 and have concluded that severe effects may result, although a direct quantitative relationship with forest productivity has not been developed (Ulrich et al., 1980; Budd et al., 1981, Tomlinson, 1981.).

Forest fertilization has been practised on a commercial scale in Scandinavian countries for a number of years (Kraus, 1981), and extensive experiments have been conducted in Canada (Rennie, 1977). These experiments have demonstrated a stimulatory effect of nitrogen, phosphorus, and potassium on forests, up to a limiting value. Therefore, increased loadings of nitrates, and perhaps sulphates, might have a positive effect on forest productivity.

Research in Scandinavia has revealed a strong correlation between available calcium in the rooting zone within a given site class and forest productivity (Viro, 1955; Dahl et al., 1961; Dahl et al., 1967; Dahl & Skre, 1971; Bolin et al., 1971; Dahl, 1975). This relationship was derived through multiple regression of large numbers of chemical and physical characteristics of forest sites against measured forest productivity. Experiments in Norway with liming, and liming and fertilizer have not demonstrated a conclusive relationship between calcium and wood production (Abrahamsen et al., 1980; Tveite and Abrahamsen, 1980; Tveit, 1980). However, work by Morrison et al. (1977) indicated that liming with calcium or magnesium alone produces little effect; however, calcium with added fertilizer produces greater wood

volumes than fertilizers alone. The specific mechanism of this response is not understood although Dahl et al. (1967) postulate several possibilities.

Changes in base saturation and leaching of basic cations have been observed in acid lysimeter studies; however, only under high acid loadings were these effects detectable over a short timeframe (Overrein et al., 1980). Field data for Ontario on base saturations are extremely limited. Attempts to measure changes in much less sensitive parameters such as soil pH, have revealed no significant trends (Linzon and Temple, 1980) except for the results of Norton (1980) and Troedsson (1980) which span up to 18 years. The changes observed by Norton were on sites with shallow textural soils while those of Troedsson span a wider range of site types. The rate of change of a soil in terms of base saturation and pH is a function of a number of characteristics including cation exchange capacity, acid deposition load, reactive soil depth, weathering rate, and rate of hydrogen uptake and hence neutralization, by vegetation and export in runoff.

3.2.2 Foliar Effects of Acid Deposition

Although the productive forest cover in Ontario provides an extremely large surface area for the interception of precipitation, little is known about specific impacts of acid deposition that are occurring on tree foliage, and the overall effects of such impacts on tree growth. Despite mention in the literature of the likelihood of effects (e.g. Jacobson, 1980 and Lindberg et al., 1981), there have been no documented field

observations of foliar damage for any tree species owing to acid deposition under ambient conditions (Cowling, 1981; Altshuller and McBean, 1981; Linzon, personal communication, 1981). However, some authors (eg. Tamm and Cowling, 1977) have suggested a number of mechanisms whereby growth losses could result either directly or indirectly through injury to foliage. These include:

- damage to surface tissues due to corrosion of the protective leaf cuticle;
- loss of control of guard cell junction as a result of changes in the pH of the cytoplasm;
- necrotic lesions developing on leaves due to high acid concentrations when dry deposition becomes wetted, or leaves alternately becoming dry and wet;
- synergistic interaction of acid rain with other atmospheric pollutants, which are known to affect foliage;
- leaching of nutrients from foliage following corrosion of cuticle;
- increased susceptibility to drought, atmospheric pollutants, disease, insect infestations, etc. following cuticle erosion and/or loss of guard cell function.

While such impacts may be occurring, it is difficult to differentiate in the field the precise effects resulting from acid deposition from those impacts which are due to various other atmospheric pollutants, and

disease, insects, or even extreme weather conditions (Jacobson, 1980).

In order to alleviate this problem, a number of researchers have conducted simulated acid rain experiments in the laboratory and in controlled field tests using a variety of agricultural crops, as well as some temperate trees such as pine, oak, birch, and poplar (Wood and Borman, 1974 and Evans and Curry, 1979). Most experiments have involved the spraying of leaves with a range of acid concentrations for varying durations. In general the apparent effects of acid on foliage in such tests are generally recorded at concentrations well above ambient levels. For example, Horntvedt et al. (1980) detected injury on birch leaves only below a pH of 3.0 and reported no apparent injuries on the foliage of coniferous species following tree irrigation with acidified water, even at a pH of 2.5 Tveite (1980a and 1980b) reported similar results with respect to foliar leaching and effects on growth due to foliar irrigation with simulated acid rain, to a pH of 2.5.

It should also be noted that under ambient loadings, there are numerous dissolved substances, including beneficial nutritional elements such as Ca, Mg, Na, etc. and toxic metals (Reuss, 1977), which may partially compensate or add to the direct effects of the acidity (Lindbergh et al., 1981 and Jacobson, 1980), but are not accounted for in simulated tests. Consequently, simulated experiments have been inconclusive in terms of providing information that can be directly related to ambient conditions.

The foliar effects of acid deposition are thought to be influenced by

leaf characteristics; for example, Shriner (1978) indicates that younger leaves may differ in their susceptibility from older leaves. As well, Evans et al. (1977) suggest that leaf morphological characteristics, such as veination, pubescence, roughness and presence of glands, probably influence the degree to which leaves become wetted by precipitation and, therefore, the degree to which they may be affected by acidity.

Leaf characteristics are particularly important with respect to the various species' abilities to act as dry deposition sinks and the interactions between dry and wet deposition. For example, dry deposition may constitute up to 60% of yearly sulphate and trace metal atmospheric inputs (Lindbergh et al., 1981). Consequently, exposure of leaves to several days of dry deposition followed by rain or fog could lead to the formation of acids on leaves. Rain duration and intensity are critical in this respect, since long, heavy rains would wash the leaves of dry deposition, while light rains of limited duration could lead to the formation of concentrated solutions. Light rain followed by evaporation could result in acid solutions on leaves many times greater than those of ambient rain, and lead to leaf cuticle erosion. Under these circumstances, antecedent conditions could be of equal or greater importance than the actual rainfall event.

Currently, there is little quantitative information on the interactions between wet and dry deposition with respect to the effects on foliage, and rate of dry deposition and accumulation on various tree species (Lindbergh et al., 1981). Data concerning the deposition and effects,

which may be positive, of particulate nitrogen compounds (Bengston et al., 1980) are especially lacking.

Specific site conditions may also play a significant role in the overall effects of acid deposition on foliage. Duvigneaud and Denaeyer de Smet (1970) reported that the uptake of nutrients by trees varies between forests, even those of equal productivity, depending upon local soil mineral availabilities. Since uptake is partially a passive, osmotic process, minerals may occur in proportion to their availability rather than their requirements by plants. Excess nutrients from mineral rich sites can be stored in various plant tissues or excreted by leaves. The leaves of trees growing on such sites, therefore, could be less susceptible to or at least better able to compensate for foliar leaching due to acid rain. Furthermore, the variations in rainfall intensity, duration, composition, and distribution with respect to the growing season and the diversity of leaf morphologies and ages, as well as site conditions, lead to a wide range of possible interactions between wet and dry deposition of mineral acids and foliar surfaces.

The lack of empirical results obtained under field conditions means that the actual ambient loadings required to produce particular injuries in specific trees and the overall impacts on tree productivity are essentially unknown at present (Jacobson, 1980). Consequently, species specific information is lacking for the various commercially harvested trees in Ontario. Issues requiring clarification and quantification include:

- the relationship between foliar injury and loss in productivity (this probably varies from species to species);

- the degree to which foliar absorption of nutrients may offset soil nutritional deficiencies (positive effects on productivity potentially could result in some cases);

- the degree to which foliar leaching of nutrients will affect productivity (i.e., variation of nutrient availability from site to site may be critical); and

- leaf injury pH thresholds for the various tree species.

The available information only tends to indicate, in a gross fashion, the relative sensitivities of individual tree species or tree species groups (i.e. hardwoods versus conifers) to acid deposition. Lang and Krupa (1978) suggest that poplar is sensitive, and birch and ash are moderately tolerant, while Evans (1980) indicates that oaks are relatively tolerant and poplars are sensitive. He also suggests that conifer needles are more resistant to acid deposition than hardwood foliage. These sensitivities correspond generally with tree tolerances to other air pollutants, such as SO_2. For example, McGovern and Balsillie (1973) report white spruce and oak to be relatively resistant to SO_2 while white birch, white pine, and trembling aspen are less tolerant.

In summary, the only study reporting direct reductions on forest productivity due to acid deposition under ambient conditions was conducted by Jonsson and Sundberg (1972). However, no numerical estimates of the loss in growth were provided. Also, Cogbill (1976) and Strand (1980) indicated that a significant correlation between forest growth and acid precipitation could not be established at the present time. Overrein et al. (1980) support this view but noted that "the effect of acid deposition [on forest productivity] must probably be of the order of at least 1 percent per annum to be detected".

3.3 ESTIMATING THE IMPACTS OF ACID DEPOSITION ON FOREST YIELDS

As stated, the detailed relationships between acid deposition and impacts on forest yields have not been well established. Consequently, while it is possible to design a complicated theoretical model incorporating numerous possible causal connections, the experimental data are not available for assessing the relation and absolute magnitude of each function. An alternative approach, one that is adopted here, is to work with less detailed empirical relationships that are, nevertheless, consistent with basic theory. These relationships are combined into a model which can accommodate major differences in soil characteristics and tree species and can be used on a sub-provincial basis for estimating the likely impacts of acid deposition on forest yields.

3.3.1 Soils Response Model - Approach

Overrein et al. (1980) state that "[the] most serious consequence for terrestrial ecosystems of regional acidification at currently observed levels...may be the increased rate of leaching of major elements and trace metals from forest soils and vegetation." They go on to say that "it seems...to be a question of proportion and time required rather than whether any ecological effects appear or not." The conceptual model presented below attempts to address the points raised by these statements.

Increased leaching caused by acid deposition of basic cations from the upper soil horizons can be supported theoretically, experimentally and by field observations (McFee et al., 1979; Overrein et al., 1980 Troedsson, 1980). The rate of leaching is dependent on a great number of physical, chemical and biological factors which are discussed in section 3.3.2 - Assumptions and Limitations. However, perhaps more importantly, the response of the forest ecosystem in terms of wood production is not understood. In fact, researchers have presented evidence supporting the full spectrum of effects from increased production to no effect to a decline in production (Jacobson, 1980). A difficulty arises in interpreting these results since timeframe, experimental conditions, and isolation of causal factors are normally not comparable.

Concentrating first on leaching of cations, some of the first work on

forest productivity, available base cations, (in particular calcium), and acid deposition was undertaken by Dahl and Skre (1971). They demonstrated a clear connection between the amount of available calcium in the upper soil horizons and the productivity of Norwegian and Finnish forest lands. This relationship has also been demonstrated for Sweden (Lundmark, 1972). In Sweden it has been estimated that an average reduction of calcium content of the humus layer of 50 kg/hectare will result in an average decrease in forest growth of 1 m^3/hectare/year. The humus layer accounts for between one half and one quarter of the total amount of exchangeable calcium in the soil (Bolin et al., 1971).

The relationship has not been reflected in some liming experiments where a growth increase is expected (Tamm & Wiklander, 1980; Tveite & Abrahamsen, 1980). However, where liming is combined with fertilization, a significant stimulatory effect is noted (Morrison et al., 1977). In these experiments, a 1 m^3/hectare/year increase in wood production was associated with an increase of 79 kg/hectare of calcium. The results were not totally consistent for all treatment combinations and the authors note that "the lack of response to Ca and Mg in the absence of N, P, and K [indicates] that deficiencies of Ca and Mg, if such exist, are at least not primary." It is likely that the relation between calcium and forest productivity is indirect, that is, calcium likely functions as a secondary factor relative to a primary controlling parameter for forest productivity (Dahl et al, 1967; Bolin et al., 1971).

If, despite the lack of detailed understanding of the processes involved,

the relationship between exchangeable calcium and tree growth is valid for the prediction of forest productivity, two questions must be answered:

(i) What is the rate of exchangeable calcium depletion due to acid deposition?

(ii) What is the precise relationship or coefficient between loss of exchangeable calcium and forest productivity?

To answer the first question, an attempt has been made in this study to estimate the rate of leaching based on a simple mass balance of net inputs and net outputs of cations to a given forest system which will maintain ionic electro-neutrality. A similar approach is presented by Overrein et al. (1980). However, in their example no consideration was given to factors such as vegetative uptake, physical weathering or nitrogen fixation. They concluded that a straight physical titration is "clearly not valid." When other factors are considered "the calculation indicates that acid precipitation may change the base saturation of soils significantly in perhaps one or a few decades."

In the model two sources of hydrogen ion input, specifically atmospheric deposition and nitrogen fixation, are considered to estimate rates of leaching of exchangeable calcium. At the outset, there is a store of basic cations in the soil mantle which may be depleted via one of two routes:

- leaching out of the upper soil layers to lower horizons or away from the site in runoff; or

- uptake of basic cations by vegetation, then incorporation in the wood and eventual removal by tree harvesting.

The following equation is based on stoichiometric mass balance reactions between incoming atmospherically deposited H^+ ions and the basic cations in the soil. The net change in soil base saturation is predicted for each time interval through this mass balance accounting.

(3.1)

COMPONENT IN EQUATION

$$BS_{j,k+1} = ((A_j \times CEC_j \times D_j \times L_j \times BS_{j,k} \times 10^6)$$ (INITIAL BASE SATURATION)

$$- (([H^+]_{,Fj} \times A_j \times D_j \times S_j \times 10^{10})$$ (NITROGEN FIXATION)

$$+ ([H^+]_{j,k} \times M_j \times A_j \times 10^7)$$ (ATMOSPHERIC INPUT)

$$+ \sum_{i=1}^{10} \frac{Y_{i,j,k}}{Y_{T,j,k}} ([H^+]_{U,i,j,k}))) \;/$$ (UPTAKE INTO WOOD)

$$(A_j \times CEC_j \times D_j \times S_j \times 10^6)$$ (TOTAL CATION EXCHANGE CAPACITY)

where: i = Tree Species (1.....10)
U = Net Uptake in Wood
j = Region (1.....64)
k = Time Period (1.....z)
F = Nitrogen Fixation
T = Sum of all Tree Species

$BS_{j,k}$ = Base saturation of forest soils (%)
A_j = Productive Forest Land (km^2)

CEC_j = Cation Exchange Capacity (meq/100g)
D_j = Bulk Density of Forest Soils (g/cc)
L_j = Active Depth of Soil (cm)

$[H^+]_{j,k}$ = Net Atmospheric Hydrogen Ion Deposition i.e., 10(-pH), (meq/l)
M_j = Atmospheric Deposition Rate (cm/yr)
$Y_{i,j,k}$ = Periodic Yield of Tree Species (cunits/yr)
$Y_{T,j,k}$ = Periodic Yield of all Tree Species i.e. annual allowable cut (cunits/yr)
$[H^+]_{U,i,j,k}$ = Net Cation Uptake into Trees (meq/cunit/yr)
$[H^+]_{F,j}$ = Hydrogen ion Concentration Generated by Nitrogen Fixation (meq/g)

Figure 3.2

Foliar Dose - Response Relationships: Forestry

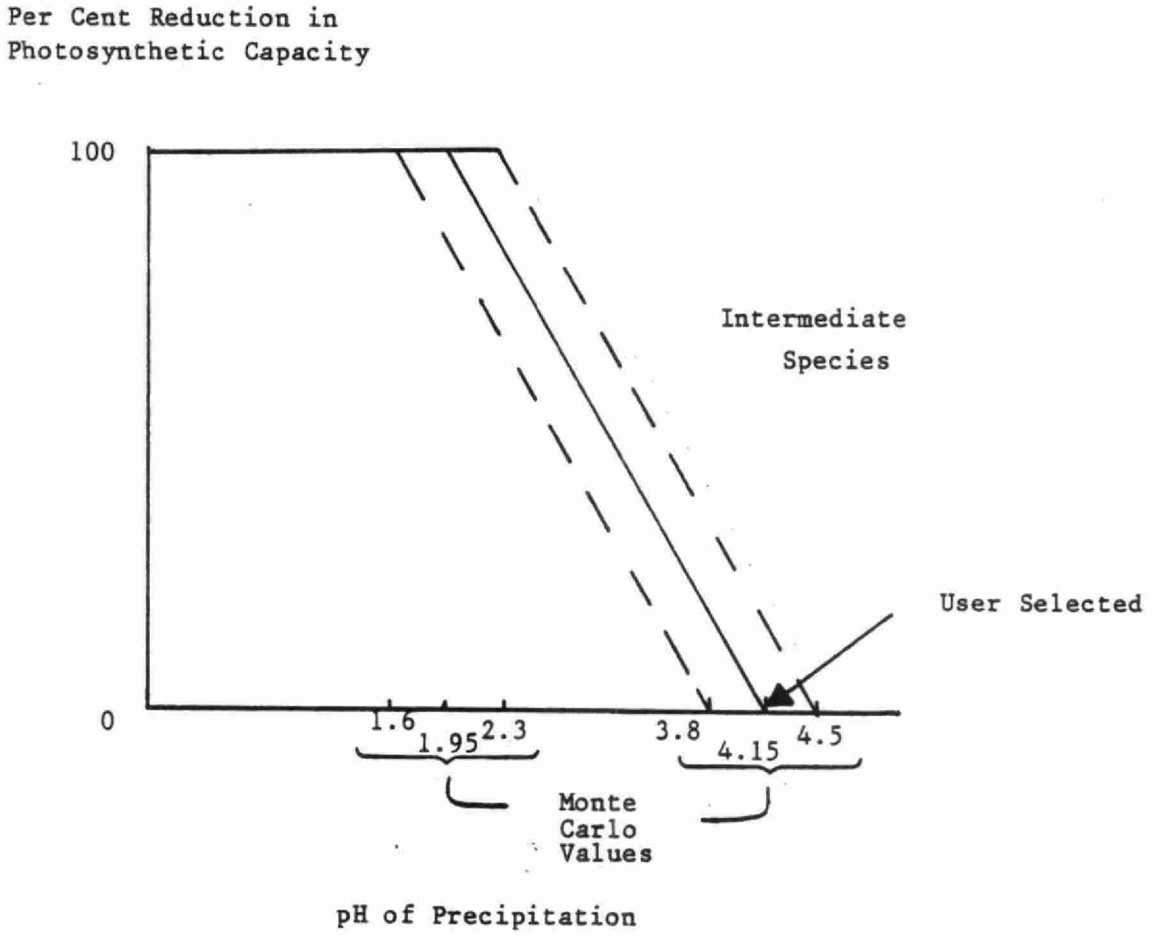
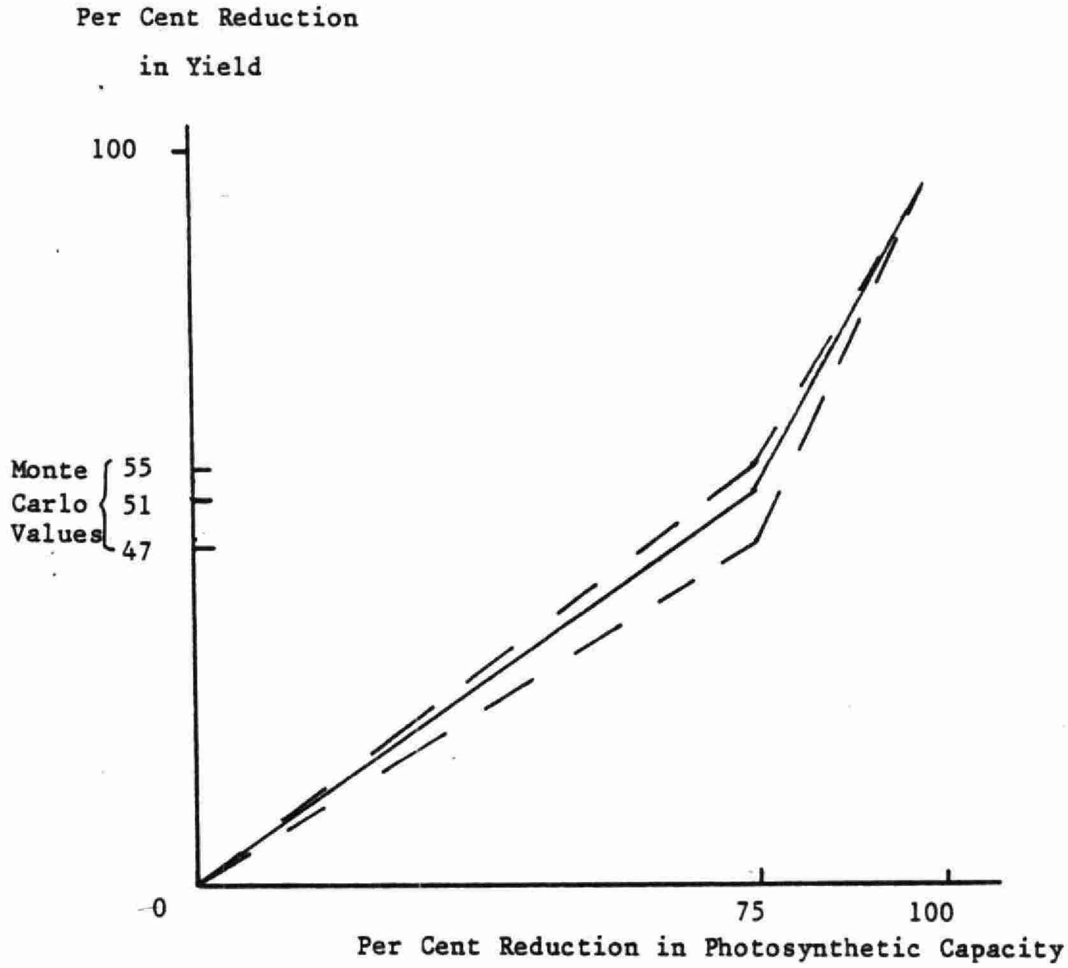


Table of Parameter Values Used in the Computational Framework

	pH of Precipitation	
100% Reduction in Photosynthetic Capacity	s: 1.6, 1.85, 2.1 i: 1.6, 1.95, 2.3 t: 1.8, 2.15, 2.5	s= sensitive species i= intermediate species t= tolerant species
0% Reduction in Photosynthetic Capacity	s: 4.1, 4.4, 4.7 i: 3.8, 4.15, 4.5 t: 3.0, 3.5, 4.0	

Figure 3.3

Yield - Photosynthetic Capacity Relationship: Forestry (All Species)



An iterative solution is obtained by selecting a particular set of initial conditions and atmospheric loadings and inserting the new base saturation $BS_{j,k+1}$ in each subsequent cycle. To predict the change in exchangeable calcium, its frequency and availability in relation to other exchangeable basic cations must be known. While this varies for each soil type, calcium is the dominant basic cation in many undisturbed soils (Morrison, 1974; Overrein et al., 1980). The following equation yields the concentration of exchangeable calcium in the upper soil horizons.

$$[CA^{++}]_{E,j,k} = BS_{j,k} \times CEC_j \times D_j \times CA_j^{++} \times 10^{-1} \qquad (3.2)$$

where: $CA^{++}_{E,j,k}$ = concentration of exchangeable (E) calcium in region j for time period k (meq/l)

The response of the forest to reduced exchangeable calcium is likely to vary from site to site and may well not be a linear relationship. Although a fixed coefficient derived by Dahl and Skre (1971) has been used in the model, nonlinear factors may be inserted as appropriate data become available. The equation relating exchangeable calcium to forest productivity presently included in the computational framework is as follows:

$$Y_{i,CA,j,k+1} = .729 \quad [CA^{++}]_{E,j,k+1} - [CA^{++}]_{E,j,k} \qquad (3.3)$$

where: $Y_{i,CA,j,k+1}$ = yield of tree species j in Region k, time period k+1 due to calcium concentration.

For Monte Carlo runs, the coefficient .729 is allowed to vary according to a triangular distribution described by the three values .568, .729, .848, where the 3 values represent the lower limit, the most probable value, and the upper limit respectively.

It has been suggested that the deposition of nitrogen and sulphur compounds may have a stimulatory effect on forest productivity (Abrahamsen, 1980). Mass balance monitoring studies indicate that nitrogen is incorporated in the forest ecosystems; approximately 70 to 85% of the nitrogen is retained (Overrein, et al., 1980). The input and output of sulphur compounds are nearly equal and often the output exceeds the input by acid deposition (Abrahamsen, 1980c). While calculations of N concentrations in foliage and forest productivity have indicated a positive relationship, sulphur does not appear to contribute to growth stimulation (Tviete, 1980a and Overrein et al., 1980). Accordingly, the response model used in this study has a nitrogen component which estimates the growth effect of a change in the deposition of nitrogen compounds. No sulphur component is included. The equation for the nitrogen effect is as follows (based on regression analysis of reported results, eg. Morrison, et al., 1977; Morrison 1974):

$$Y_{SNRP} = 2.76 \times 10^{-4} \times [NO^{-}_{3}]_{j,k} \tag{3.4}$$

where: $Y_{i,N,j,k}$ = yield of tree species i in region j for time period k due to nitrogen fertilization N (%)

$[NO^{-}_{3}]_{j,k}$ = nitrogen concentration of precipitation (meq/m^2)

For the Monte Carlo runs the coefficient 2.74×10^{-4} is allowed to vary according to a triangular distribution with 1.5×10^{-4} as the lower limit, 2.76×10^{-4} as the most probable value, and 4.5×10^{-4} as the upper limit.

An upper limit of .1908/kg/hectare of nitrogen has been assigned to this linear relationship. Beyond this value it is assumed that nitrogen will no longer be a limiting element and further additions will not cause further positive responses in forest production. This upper limit and indeed the slope of the response curve will likely be highly sensitive to the characteristics of each site though this is not allowed for at present. The assumed relationship has been derived from the results of forest fertilization experiments on a variety of site types and is the net response of the forest to fertilization (i.e. includes uptake by subordinate vegetation, internal cycling and transfer effects, and change in total standing biomass and nitogren concentration thereof).

A final component of the soil response model is a relationship between aluminum in soils, root vigour and survival, and tree productivity. According to the cation mass balance equation, the loss of exchangeable calcium is a continuous linear function. Based on the relationship between soil pH and base saturation (Kramer, 1976):

$$\text{soil pH} = (BS + 1.5)/0.33 \qquad (3.5)$$

At zero base saturation, the soil pH is equal to 4.55. Beyond this point, it is assumed that no further losses of exchangeable calcium can occur and therefore there will be no further effect on forest yield. Currently however, many forest soils in Ontario are at pH 4.5 or lower. Additionally, several authors have drawn attention to the potential toxicity of aluminum and perhaps manganese at soil pH values below 5.0 (Tomlinson, 1981). Research on this impact is underway; however, it is focussed on the effects on specific plant structures (ie. root development) and susceptibility of affected areas to various factors (ie. drought, disease, etc.) Accordingly it is not yet possible to develop a specific empirically based relationship between aluminum and manganese availability and forest productivity. As an interim step, therefore, the following general structure is presented and incorporated in the model so that as the necessary data become available they can be entered into the analysis.

Aluminum availability is a function of soil pH, the physical and chemical nature of the soil matrix, the presence of organic substances, and the acid loading (Ulrich, et al.,1980). The equation to predict aluminum availability might take the form:

$$[Al] = (a(pH_s)/b(OC_s) \times pH_p + c \quad (3.6)$$

where [Al] is the available aluminum

a, b and c are constants

pH_s is the pH of the soil

OC_s is the organic content of the soil

PH_p is the pH of the precipitation

Change in forest yield would be predicted by an equation of the form:

$$Y = d([Al]) + e \quad (3.7)$$

where Y is wood yield

d and e are constants.

The net response of the forest to the soil impacts of acid deposition is predicted by summing all negative and positive impacts predicted by the above equations. It is important to note that the changes predicted by the soils component are permanent and are carried over or cumulated from year to year. In contrast, the foliar effects are considered ephemeral and are not cumulative.

3.3.2 Soils Response Model - Assumptions and Limitations

The following is a brief discussion of the major assumptions of the soils model, the limitations which they impose on the accuracy of the predicted effects, the level of uncertainty and the potential quantitative effect

of these limitations on the estimated changes in yield. Factors which may not be considered by this approach are also noted.

1. The reaction of basic cations with hydrogen ions.

Wiklander (1980) examined the response of soils to H^+ loads and noted that with increasing acidity down to about pH 5, the one to one proportionality between the exchange of input H^+ and basic cations (i.e. base saturation) was reasonable. However, at lower pH values, the remaining basic cations are increasingly difficult to displace and the one to one proportionality no longer holds. The precise relationship is defined by a variety of factors which are beyond the scope of this report. Anions also play a key role in this exchange process. The migration of basic cations is dependent on the presence of an associated anion such as SO_4^{-2} or NO_3^-. Because NO_3^- may be uptaken by vegetation, its effect on leaching may be reduced. Currently, the primary focus is on sulphates with respect to soil acidification. The assumptions of a straight line relationship and availability of mobile anions will tend to overestimate damages, in particular, below soil pH 5.

The one to one proportionality also assumes that all acidic deposits undergo complete reaction with the soil matrix prior to runoff or leaching through the soil profile. During heavy rainfalls and snow-melt, the soil and precipitation may not reach an equilibrium solution. This limitation will lead to an overestimate of the forestry effects.

2. The depth of the reactive soil layer.

A value of 25 cm has been used as the depth of the reactive soil layer for all sub-regions and is based on the distribution of the roots in the soil horizon and known soil horizon properties. (This value can be changed in the model.) While most tree roots are located in this layer (D. Fayle, pers. comm.), the role of deeper tap roots in transporting basic cations from greater depths is uncertain and has been discounted. This assumption will lead to an overestimate of the damages if these basic cations are available to the trees and/or are released through foliar leaching to the forest soil.

Depending on soil development and history, the 25 cm value could vary considerably between sites from as little as 2 - 3 cm to as much as 40 cm or more.

If the assumed soil depth is too shallow it would lead to an underestimate of the damages and vice versa for an assumed soil depth that is too high.

3. Carbonate buffering.

The soil acidification model assumes that all buffering is contributed by cation exchange of aluminum silicate minerals and organic matter resulting in shifts in base saturation. Solutions of carbonates in the soil mantle will also contribute to acid neutralization and will reduce the rate of base saturation reduction. In most upper soil horizons on the Precambrian Shield, available carbonate is minimal; however, in areas

with extensive fine silts and clays, or with shallow overburden over limestone bedrock, or with surficial ground water discharge, significant quantities of carbonates may be present. By excluding carbonates from the soil acidification model, the rate of soil acidification will be overestimated. This weakness could be refined when sufficient soil chemistry data become available to quantify carbonate content of the reactive soil layer on a site specific basis.

4. Addition of basic cations through soil weathering and atmospheric deposition.

"Weathering rates vary dramatically with type of minerals, amount of precipitation and other factors." (Overrein et. al, 1980) As the lime potential of the rainfall decreases the rate of weathering increases (Stuanes, 1980). Estimates of weathering for resistant bedrock sites with shallow overburden in Norway range from 40 to 85 meq./m^2/yr. for calcium and magnesium have been reported (Overrein et. al, 1980). However, at pH 2 applied rainfall, a value of 320 meq./m^2/yr. was recorded. Associated with the lime potential of precipitation is implied the atmospheric deposition of basic cations. This input has not been explicitly considered and some researchers feel that most basic cations deposited result from local redistribution by wind and do not represent a net input to the system (P. Dillon, pers. comm. and J. Kramer, pers. comm.). The exclusion of a weathering component will tend to overestimate the damages.

5. Hydrogen cycle and balance.

The hydrogen cycle is a fundamental process in any biological system. However, due to the ubiquity and mobility of this ion, a comprehensive understanding of its flow through ecosystems has yet to be achieved (Ulrich, 1980). It is assumed in this study that any excess hydrogen in the wood molecules has resulted in a net reduction in the acid load to the forest soil. This reduction is affected somewhat by the uptake of basic cations in the wood and therefore a net reduction was calculated by subtracting basic cation uptake. A considerable proportion of the hydrogen ion likely originates during photosynthesis from the combination of CO_2 and H_2O resulting in no net gain or loss of acidity. However, other soil and plant mechanisms such as ammonium uptake by roots and nitrification which may affect the soil acid balance have not been explicitly included since they may not effect a net alteration to the system chemistry. The H^+ ion uptake can be modified as these internal chemical mechanisms become better understood quantitatively and with respect to overall system mass balance. Due to the uncertainty associated with this assumption it is not possible to state whether it likely leads to an over- or underestimate of damages.

6. Current wood production estimates reflect non-anthropogenic nitrogen and hydrogen loads and current exchangeable calcium.

The allowable cuts estimated by the Ministry of Natural Resources are not based on an explicit consideration of the impact of acid deposition. If

acid deposition has been affecting forest productivity in the past then these effects will be incorporated implicitly in the estimated allowable cuts. Unfortunately, historical data on deposition and soil conditions do not exist and it is not possible to estimate what the allowable cuts would have been in the absence of acid deposition up to and including the base year, 1979.

The importance of this lies not in estimating the historical impacts of acid deposition, since nothing can be done about them now, but in the implications for the estimates of future impacts. In this study, it is assumed that the annual allowable cuts are based on current soil conditions and non-anthropogenic loadings of hydrogen and nitrogen. The first of these assumptions will not affect the estimates of impacts since future yields are related to changes in the exchangeable calcium in the soil and not to absolute levels. Insofar as there was some positive impact of anthropogenic nitrogen on forest productivity in 1979 then the approach taken will tend to overestimate future positive impacts. This will be counter-balanced by an error in the opposite direction regarding the possible negative impacts of hydrogen, some of which may have been occurring in the base year. However it is not possible to say what the net effects of these assumptions will be.

7. Lack of direct evidence of acid deposition impacts on forest systems.

As mentioned previously, opinions differ as to whether the effects of

acid deposition on forest productivity are positive or negative. It has been suggested that positive effects are likely in the short term and the overall long term effects will be negative (Tveite, 1980a; Overrein et al., 1980). Efforts to detect long term changes in forest productivity have so far failed to provide conclusive evidence (Jonsson, 1977); however it should be noted that relatively large changes (i.e. †1%/year) would be required for this detection (Strand, 1980; Jonsson & Sundberg, 1971 and Bolin et al., 1971).

The values of the coefficients relating calcium and nitrogen to forest productivity have been based on:

a) comparison of sites with varying exchangeable calcium and forest productivity;
b) analysis of the stimulatory effects of calcium with fertilizer additions;
c) the observed increased leaching of basic cations with acid loading; and
d) the positive response of forests to nitrogen additions which suggests that atmospheric depositions of nitrogen will also stimulate forest growth.

The precise values of these coefficients may vary considerably with site characteristics and it is therefore not possible to determine whether the values used in the study over- or underestimate the effects.

8. Change in species composition with acidification.

Species composition and dominance of a particular forest stand is the result of a number of factors, not the least of which is soil characteristics. Soil acidification could lead to a species shift which might alter the potential yield and value of the wood produced from a given site. This factor is not considered in the model.

9. Substances other than aluminum and manganese may be toxic.

Soil acidification can lead to the mobilization of heavy metals which are toxic to plant growth (Overrein et al., 1980). In addition, long range transport and deposition of these metals and other toxic organic compounds may be occurring. The cumulative effects of such phenomena have not been considered in the model and this will lead to an underestimate of damages.

10. Availability of basic biological, chemical and physical data for site districts.

The required input data for the model have been derived through diverse sources. However, a comprehensive data base is not available. Broad generalizations have been required to describe conditions in the site districts and a quantitative weighting of terrain units within a site district has not been attempted. The proximity of the estimated values to the actual conditions can not be estimated until more detailed work is

undertaken. It is not possible to determine whether the values predicted will lead to an under- or overestimate of effects.

11. Autochthonous generation of H^+.

The oxidation of various compounds, and in particular sulphur compounds, can lead to the generation of H^+ ions (Overrein et. al, 1980). The magnitude of such effects will depend on the availability of these compounds and the rate of weathering. The nitrogen fixation component is also a source of autochthonous H^+; however, the associated chemistry is poorly understood. Accordingly, this component has not been activated in the current model; further clarification concerning the net effect, if any, of this process is required to provide the necessary coefficients. These factors have not been included in the soils model and may lead to an underestimate of the damages.

12. Effect on seed germination and seedling establishment.

Both stimulatory and repressive effects have been reported for seed and seedling growth (Overrein et. al, 1980). Stimulating effects could lead to both positive and negative effects. Sapling competition can reduce overall production of merchantable timber. However, insufficient regeneration on many sites has led to declines in merchantable volumes. Since too much or too little seedling development can have negative effects, the net effect of this impact will depend on site conditions. Neither the soil nor foliar response models account for this factor.

3.3.3 Foliar Response Model - Approach

Initially each of the dominant tree species harvested in Ontario was rated according to three sensitivities (sensitive, moderate, tolerant) based on the work of Evans (1980), Evans et al. (1978), Lang and Krupa (1978), Tveite (1980b), and Wood and Borman (1974, 1977). However, as the harvest data for the Province is often for broad species groupings (which may contain species of varying sensitivities), the harvest groups were rated according to the dominant species harvested and then assigned to sensitivity classes accordingly. For example, red pine was rated initially as intermediate; however this species was included with white pine in the sensitive tree group due to the predominance of the latter species in the overall harvest in Ontario. Similarly red maple was included in the sensitive maple-yellow birch group rather than as intermediate sensitivity as initially indicated. The final ratings are shown below:

TOLERANT	INTERMEDIATE	SENSITIVE
Spruce	Jack Pine	Maple
Cedar	White Birch	Yellow Birch
Fir	Ash	White & Red Pine
Oak	Elm	Poplar

Simulated studies indicate a tendency for foliar injury to occur, or at least become observable, at a particular pH level. Consequently, three threshold pH levels were estimated based on the literature referred to above, for the three sensitivity groupings based on the available data for trees. The pH thresholds are 4.5 for

sensitive species, 4.15 for intermediate species and 3.5 for tolerant species. When operating the computational framework the user has the option of changing these values by entering a proportion by which they are automatically multiplied.

pH values at which a 100% loss in photosynthetic capacity occur have also been estimated. These are 2.15 for sensitive species, 1.95 for intermediate species and 1.85 for tolerant species. If the Monte Carlo option is utilized then the pH values at which 100% and 0% damage occurs are selected at random from a range of values as shown in the table under Figure 3.2. All values in the range are considered equally likely. Figure 3.2 gives a graphical representation of the relationship between pH of precipitation and for percentage reduction in photosynthetic capacity for intermediate species. The broken lines show the range of values used in the Monte Carlo simulation.

As stated previously, there are no reliable data which demonstrate the precise relationship between the degree of foliar damage due to acid deposition and the rates of change in overall productivities for the various tree species. For example, it is not known whether such a relationship is direct, whether it is exponential, or whether there is an initial lag period corresponding to zero or insignificant effects on productivity when injury occurs to only a small proportion of leaf cover. There is an indication that relationships may in fact vary from species to species. Brisley et al. (1959) reported a direct relationship between reduced leaf area due to SO_2 fumigation and productivity for cotton, and pointed to other studies which showed alfalfa could lose 5% foliage

before effects on yield could be detected. These are agricultural crops, and trees may exhibit similar responses; however, specific information for trees harvested in Ontario or elsewhere is unavailable. Consequently, it is assumed for the present time that the relationship obtained for cotton applies to all tree species. The specific relationship is shown in Figure 3.3 by the solid line. Variation in the relationship considered in the Monte Carlo runs are shown by the broken lines with all values within the range indicated considered equally likely. This relationship, currently incorporated in the computational framework, is not based on data directly applicable to the acid deposition situation in Ontario due to the species and pollutant involved; however, it was the only one available to the consultants (S. Linzon, pers. comm.; D. Fayle, pers. comm.).

The solid line in Figure 3.3 shows that for every 1% reduction in leaf area, there is a corresponding 0.68% reduction in productivity up to a loss in leaf area of 75%. (Beyond that the rate of loss is increased so that 100% loss in leaf area gives a 100% loss in yield. It is most unlikely that acid deposition levels will give results falling in this latter segment). This relationship is applied to all three tree sensitivity groups once their respective threshold pH levels are reached. However, users of the computational framework have the option of introducing a proportional adjustment to the values for a percentage reduction in yield that corresponds to a 75% reduction in photosynthetic capacity. Adjustments for all other reductions in photosynthetic

capacity are compiled by interpolation.

3.3.4 Foliar Response Model: Assumptions and Limitations

Due to the lack of information with respect to foliar damage to trees under varying acid deposition conditions, a number of assumptions have been necessary which seriously limit the confidence that can be placed in the estimates of foliar impacts.

1. Simulated tests

The results of simulated tests (i.e. threshold pH levels) have been relied upon in this study. As stated earlier, such experiments are generally based on laboratory situations and the results may differ from those obtained under natural conditions. The dose-response relationships used ignore site specific considerations and the synergistic effects of other pollutants and environmental factors. In addition, until just recently, widely accepted experimental procedures for conducting simulated acid deposition dose-response studies were not available and experimental conditions varied significantly from one researcher to another (E. Piche, pers. comm.).

Foliar damage is likely determined to a large extent by stochastic properties of local climate including frequency, intensity, and duration of precipitation events, frequency of dew and fog, relative humidity and temperature. To address these factors an event-specific simulation model

would be required to predict foliar damage. This approach would be costly in terms of required input data and computer and operator time and was not feasible for this study.

Each of these considerations could lead to over- or under estimates of damages and their combined effect can not be ascertained generally for all regions.

2. Species aggregation

The data have been applied to three broad species groups that contain species which, in reality, may differ significantly in their sensitivities. Individual trees within a stand will vary in sensitivity according to genetic characteristics and site and climatic region.

3. Foliar injury and productivity

The relationship of percent reduction in leaf area to percent loss in productivity for cotton may not be true for all or any tree species, as has been assumed in this study. Also, the relevant loss rates for the various species actually may vary widely between and within species and may not be linear. In particular, the harvestable portion of cotton is annually produced and is associated with the fruit; whereas the trunk or stem of a tree is the essential component harvested and accumulates over a number of years. Undoubtedly, a relationship between foliar damage and annual production exists and until a more precise relationship applicable

to tree species in derived, this factor is proposed. A high degree of uncertainty exists concerning this relationship and it is not possible to suggest whether the factor used will over-or underestimate the impact.

4. Leaf sensitivity

Leaves of individual tree species may vary in their sensitivity to acid deposition at different stages of their development and may also differ in their tolerances depending upon actual site conditions. To deal with this aspect, a seasonal or temporal component reflecting leaf development would need to be added to the simulation of climatic conditions discussed in number 1 preceding. Such factors are not accounted for in the model.

5. Leaf exposure to precipitation

No allowance has been made for the fact that evergreen needles are exposed to year round precipitation while deciduous leaves are only exposed during the growing season. In addition, foliar effects are assumed to be ephemeral for all species. Foliar damage to conifers may impair photosynthetic capacity for the life of the needle (i.e., 3 - 8 years).

It is not possible to determine precisely the direction or size of error introduced by these factors. Clearly, the relationships between acid deposition, photosynthetic capacity of leaves by species, and tree growth

demand further research.

3.4 APPLICATION OF THE FOREST MODELS TO ONTARIO

As mentioned in Section 3.1, Hills' Site Classification for Ontario has been used to segregate the province into regions comprising relatively uniform response ecosystems. For each Site District, input data have been developed based on county soils maps, geological and physiographic maps and the results of site specific studies. Ideally, the values used should represent a weighted value derived from detailed site analyses of individual terrain units within a site district. However, information at this level of detail is not available and best estimates based on the study team's experience and the available data were used.

Forest productivity estimates according to the annual volume of merchantable timber produced have been derived for all of the Province south of the 50th parallel by the Ministry of Natural Resources (MNR). These estimates were developed using airphoto interpretation and field checking and other available information. From these estimates the Ministry of Natural Resources has determined annual allowable cuts for each tree species for each of its administrative districts. To use these annual allowable cut figures for productivity estimates in this study, it was necessary to prorate the figures for each administrative district to generate comparable figures for each site district. This proration was based primarily on area distribution with minor modifications where major variances in site quality were known. Forest productivity estimates for

Ontario north of the 50th parallel were obtained from Department of Lands & Forests (1963).

To generate estimates of changes in forest productivity, these values for allowable cuts are used in each region for the first year. The yield in each subsequent year is derived by subtracting the estimated decrease or adding the estimated increase in productivity for the given year to the yield of the preceeding year.

Details of the atmospheric loadings of acid and nitrogenous compounds required as inputs to the model are given in appendix A. At present only wet disposition is included.

3.5 THE ECONOMIC VALUE OF THE IMPACT OF ACID DEPOSITION ON ONTARIOS'S FORESTS

The demand for wood by the forest products industries is derived from the demands for paper and lumber. In this study it was assumed that, in the event of a decline in forest productivity due to acid deposition, the forestry industry will still utilize the same total quantity of wood, but will have to obtain some of it from higher cost sources. In some cases new roads might be built to open up forest stands that would not otherwise have been harvested so soon. Additional camp costs and tree removal costs might also be incurred because of the reduction in the size of trees harvested and hence the greater area required to be cut annually. Likewise, some of these costs might be reduced if forest productivity should increase as a result of acid deposition.

Table 3.1

REGIONAL WOOD COSTS - 1976 DOLLARS

NORTHERN ONTARIO

Item	Symbol Used in Eq. 3.8	Dollars per Cunit Range	Dollars per Cunit Average
Total Wood Costs including Overhead,			
Delivered at the Mill	(TWC)	60-90	80
Stumpage and Royalties	(SR)	5- 6	5
Total Costs before Stumpage and Royalties		55-85	75
Cost Components			
1. Extraction Costs:		40-50	
- camp costs	(CC)	1-10	
- falling and bucking	(FB)	12-17	
- delivery cost (excluding road costs):			
- stump to roadside	(STR)	6- 9	
- road to mill	(RTM)	11-16	
2. Road Costs:			
- primary and secondary road construction	(RC)	3- 8	
- primary and secondary road maintenance			
3. Equipment Costs (Depreciation and Leasing)	(EC)	T/E	
4. Administration Costs	(AC)	5-10	
5. Silviculture (including spraying)	(S)	T/E	

T/E means included in total extraction costs.

Source: Peat, Marwick (1977)

Thus, the approach taken to estimating the economic value of acid deposition impacts on Ontario's forests assumes that the effect on the total quantity of wood extracted will be unchanged and only the costs of extraction will be affected. This seems reasonable given the relatively modest forest impacts anticipated within the 22 year time horizon of the study (1979-2000) and the fact that, in most of the province, the actual cut of each species is less than the allowable cut and is likely to remain so until the next century.

Wood costs, including overhead, delivered at mills in Northern Ontario were estimated in a study by Peat, Marwick (1977); information on costs was obtained from company sources, industry associations and consultants to the industry (See table 3.1).

The various components of total wood costs (\$ per cunit) are given in equation 3.8.

$$TWC = SR + CC + FB + STR + RTM + RC + EC + AC + S \quad (3.8)$$

Each of these cost components could be affected by changes in tree size at maturity.

Let A_t = proportional change in tree size due to acid deposition in year t of harvesting.

K_i = proportional change in costs for component i due to a change in tree size.

Then $$TWC_t = -A_t(K_{SR} \cdot SR + K_{CC} \cdot CC + K_{FB} ; FB + K_{STR} \cdot KTR + K_{RTM} \cdot RTM + K_{RC} \cdot RC + K_{EC} \cdot EC + K_{AC} \cdot AC + K_S \cdot S) \quad (3.9)$$

In the absence of specific information the following assumed values of K_i have been incorporated in the computational framework:

$K_{SR} = 0$ $\quad K_{EC} = 0$ (included in total extraction costs)

$K_{CC} = .25$ $\quad K_{AC} = 0$

$K_{FB} = 1$ $\quad K_S = 0$ (included in total extraction costs)

$K_{STR} = .5$

$K_{RTM} = 1$

$K_{RC} = 1$

Substituting the values for the various cost components from Table 3.1 and the above values of K_i into equation 3.9 gives:

$$TWC = -38.63 \times A_t \tag{3.10}$$

Equation 3.10 expresses the relationship between the change in total wood costs and the proportional change in tree size at harvesting in terms of 1976 dollars. The same relationship in 1980 dollars is given in equation 3.11. (Annual inflation rate of 8.9% derived from the Selling Price Index for Wood Industries, Statistics Canada.)

$$TWC = -54.33 \times A_t \tag{3.11}$$

The computational framework incorporates 3.11 and the proportional change in tree size at harvesting is estimated by the biological models described in the previous sections in terms of the change in forest productivity.

Unfortunately no detailed forecasts of actual harvest are available for Ontario. The only forecast prepared by the Ministry of Natural Resources (MNR) gives highly aggregated equations for predicting roundwood demand for pulpwood production (equation 3.12) and logs and bolts (equation 3.13). (Source: Ministry of Natural Resources, April 1972.)

$$Y_t = 1.810 + 0.067 \,.\, t \qquad (3.12)$$

$$Y_t = 1.313 + 0.019 \,.\, t \qquad (3.13)$$

where: Y_1 = pulpwood in year (for 10^6 units)

Y_2 = logs and bolts in year (10^6 units)

t = time (years)

These equations were estimated from data on annual production from Crown and patented lands for the period 1940-1966. The Ministry has used these equations to project the demand for roundwood to 2020.

By adding equations 3.12 and 3.13 a third equation, 3.14, is obtained which gives an estimate of total roundwood production in Ontario. (A factor of 0.9^{-1} is included for each region to allow for the fact that, according to MNR, pulpwood, logs and bolts account for about 90% of all types of roundwood.)

$$Y_t = [3.123 + 0.086t] \,.\, 0.9^{-1} \qquad (3.14)$$

where: Y_t = total roundwood production in year t (10^6 units)

Equation 3.14 provides an estimate of the rate of increase in roundwood production in Ontario over time:

$$\frac{dY_t}{dt} = .0956$$

This value is used in the computational framework to project the actual

harvest of each species in each of the 64 regions where the actual harvest is currently less than the assumed allowable cut. In the few cases where the projected actual cut would meet and exceed the current assumed allowable within the next 20 years, the predicted actual harvest is constrained in the following way. Actual harvest is permitted to grow beyond the annual allowable cut for 10 years (to allow for the harvesting of over-mature timber) and then reduced at the same rate of growth, now negative, until the annual allowable cut is reached. After that time, actual cut and allowable cut are assumed to remain constant.

In those cases where actual cut already exceeds allowable cut, the actual cut is projected to decline at a constant rate over 10 years until the allowable cut is reached. After that time actual cut and allowable cut are assumed to remain constant.

This method of projecting actual harvest is unsatisfactory in that it is not based on projections of the relevant economic, biophysical and management factors. However, the results are consistent with the highly aggregated projections of the Ministry of Natural Resources. The economic value of the impact of acid deposition on Ontario's forests is then estimated by multiplying the forecasted wood harvest by the estimated change in the cost of harvesting due to acid deposition.

Chapter 4

AGRICULTURE

CHAPTER SUMMARY

The effects of acid deposition on agricultural productivity are discussed with reference to the literature. Soil effects are approached by assuming that farmers will adjust their use of soil amendments to counteract the effects of acid deposition (i.e. alter application rates of nitrogen and sulphur fertilizers and of lime). Foliar effects, which may be positive or negative depending on the crop and the rainfall pH are considered separately.

Data sources and a methodology for projecting agricultural yields are described. All of the assumptions for estimating soil and foliar impacts and their economic value are explained. These form the agricultural component of the computational framework.

4.1 INTRODUCTION

Agriculture in Ontario is extremely important economically and socially. In some respects, more is known about the potential effects of acid depositon on agriculture than on forestry and there are indications that, depending on the crop, some effects could be positive and some negative. For all of these reasons agriculture merits close consideration in this study.

4.2 AGRICULTURAL PRODUCTIVITY AND THE EFFECTS OF ACID DEPOSITION: BACKGROUND

Soil acidification is not a new problem for farmers. The use of nitrogen fertilizer causes relatively rapid acidification of agricultural soils which can lead to reduced crop yields. As a result, the regular application of lime is practised where large quantities of fertilizer are used and/or the natural soils have a low buffering capacity. The acidification of agricultural soils and crop responses has received considerable attention and is relatively well-understood.

Forestry and agriculture are quite similar in many respects except that in forestry, the period required for the crop to mature is much longer. Accordingly many of the soil acidification impacts discussed in Chapter 3, Section 3.2 are equally applicable to agricultural production. However, several differences are worth noting.

Agriculture is generally practised on better quality sites as compared to forestry. The soils are often deeper, more fertile, have a higher buffering capacity and are more intensively managed. Therefore, their natural susceptibility to acid deposition is somewhat reduced in general. However, the more frequent and intensive harvest of biomass and the extensive use of fertilizers tend to accelerate the depletion of basic cations in the soil. In addition, because the lands are generally more intensively managed, soil amelioration is often carried out which may interrupt and reverse the natural processes which might be ongoing in a

forest ecosystem.

Stimulatory effects of acid deposition due to the addition of nitrogen and sulphur compounds have been predicted by several authors (Cowling, 1981; Abrahamsen, 1980). These compounds, however, will only be stimulatory if they are in sufficiently limited supply to constrain growth. On agricultural soils, the application of nutrients is regularly practised, and therefore, the availability of compounds such as nitrogen and sulphur may be higher than in forest systems.

The theory of basic cation leaching is equally valid for agricultural soils although precise field measurements may not be available. Measurements of actual changes in agricultural soils due to acid deposition have not been attempted due to the frequent disturbances which they experience (i.e. through ploughing, fertilization, liming, etc.).

As is the case with forest vegetation, information on the specific foliar impacts of acid deposition on agricultural crop productivity is quite sparse and much of the existing data have been derived from simulated tests rather than from direct observations in the field under ambient conditions (Lee, et al., 1980; and Altshuller & McBean, 1981). Despite the wide variety of agricultural crops, the majority of simulated experiments have concentrated on just a few species. For example, a relatively large proportion of the existing information has been collected on bushbeans and soybeans (Irving and Miller, 1977 and 1978; Evans et al., 1977 and Evans, et al., 1980) but data on various fruit,

leaf, grain and root crops are generally lacking.

To date, such important factors as the effects of acid deposition on various plant growth stages during the growing season and on different plant parts have yet to be determined. The latter is of particular importance since crop yields vary widely in terms of the actual plant parts harvested (eg. the root of carrots, the leaves of lettuce, the fruit of tomatoes). For grain and fruit crops, the effects of acid deposition on reproductive structures is critical (since most crops are at the same stage of development over large areas) but are largely unknown (Jacobson, 1980). The effects on plant foliage may be important for all species due to the potential for affecting overall growth (see Forestry - Background to Foliar Aspects, section 3.2.2). In regard to this point, however, Lee, et al. (1980) indicate that yield changes due to acid deposition for some crops are not correlated with leaf injury and suggest equal or better than normal yields might be realized when leaves are damaged.

A summary of recent experiments on agricultural crops in Jacobson (1980) reveals a number of contradictory results in terms of yield effects, i.e. both increased and decreased yields are reported for the same crop species subjected to similar pH loadings, as well as foliar damage with no effects on growth in some cases and decreased growth in others.

The question of the stimulatory effects of acid deposition on plant growth requires comment. Lee (1981) states that various plant parts

could be affected differently and that acid deposition might change the allocation of energy within plants. Injury to leaves during a particular stage of a plant's development could reduce the competition between the vegetative and reproductive parts for photosynthate for example, and thereby stimulate flowering and/or fruiting (Jacobson, 1980). Stimulation of yields could also result from the absorption of sulphates and nitrates by foliage.

The problem of dry deposition, its interaction with wet deposition and its effect on foliage and agricultural crop growth is poorly understood (Lindbergh et al., 1981 and Krupa, 1981), especially with respect to particulate nitrogen compounds (Bengston et al., 1980). (See Section 3.2.2).

Current information on the aspects cited above is inconclusive; a great deal of additional research needs to be directed to understanding and quantifying these various phenomena before firm conclusions can be drawn (Jacobson, 1980 and Lee, 1981). However, despite the lack of data with respect to the specific responses of individual plants to the many variables associated with precipitaton, the study by Lee, et al. (1980), which examined the growth and yields of 35 agricultural crops under simulated acid rain pH levels of 5.6, 4.0, 3.5 and 3.0, indicates that crops may fall into a number of relative sensitivity groups in terms of the effects on overall yields.

These sensitivity groups are shown below:

Crops	Sensitivity Rating
Root Crops	Most Sensitive
Leaf Crops	
Cole Crops	
Tubers	
Legumes	
Fruit	
Bulbs	
Grains & Forage Grasses	Most Tolerant

Stimulatory effects on productivity were reported for the last four groups, even at a pH of 3.0. The overall results suggest that monocotyledons are less susceptible to acid deposition than dicotyledons.

Although these results were derived from simulated tests conducted during only one growing season, and in one soil type, and, as yet, have not been replicated, the study by Lee *et al.* (1980) is the most comprehensive investigation to date on the basis of numbers of crops and range of pH values considered. Consequently, the general yield - dose relationships generated in the Lee, et al., (1980) study have largely been incorporated in the computational framework, supplemented by additional research data, where available, to determine direct acid deposition impacts on yields of agricultural crops. As improved estimates of these relationships become available they can be substituted for those currently used.

4.3 ESTIMATING THE IMPACTS OF ACID DEPOSITION ON AGRICULTURAL YIELDS

4.3.1 Soils Response Model - Approach

Since soil amendments are regularly added by farmers to enhance crop production and to offset unwanted side effects of fertilizers, it is reasonable to assume that they will likewise attempt to offset any negative effects on the soil of acid deposition. In order to estimate the damages incurred by a farmer, a prediction of the increased quantity or frequency of soil amelioration is necessary. To undertake this prediction, it has been assumed that the farmer currently is maintaining his land at the optimum base saturation and pH for the crops he raises and will wish to maintain this current situation. As is the case with the soils model for forestry, a 1:1 proportionality between H^+ input and the leaching of basic cations is assumed. It is assumed in the model that the farmer increases the quantity of lime which he applies to his fields to offset the acid deposited since the last application. This is stated by equation 4.1.

$$L_t = H^+_t - {}_nH^+_t \tag{4.1}$$

where: L_t = additional lime required in year t to neutralize atmospheric acid deposition (meq)

H^+_t = total load, in year t, of H ions (meq)

${}_nH^+_t$ = estimated natural H ion load, in 1979 (meq)

The atmospheric deposition of nitrogen, and in some cases sulphur, is likely to be beneficial to plant growth. Rather than estimate the value of this source of fertilizer in terms of increased crop yield, the savings which farmers realize by not having to buy and apply the chemicals themselves are estimated (see Equations 4.2 and 4.3).

$$F^n_t = N_t - {}_nN_t \tag{4.2}$$

where: F^n_t = reduced nitrogen required from fertilizer application in year t (meq)

N_t = total atmospheric nitrogen load in year t (meq)

${}_nN_t$ = estimated natural atmospheric nitrogen load in 1979 (meq)

$$F^s_t = S_t - {}_nS_t \tag{4.3}$$

where: F^s_t = reduced sulphur required from fertilizer application in year t (meq)

S_t = atmospheric sulphur load in year t (meq)

${}_nS_t$ = estimated natural atmospheric sulphur load in 1979 (meq)

4.3.2 Soils Response Model - Assumptions and Limitations

1. Soil and crop management by individual farmers.

The analysis assumes that each individual farmer is, consciously or unconsciously, optimizing his application of soil amendments. While this may be true for some farm operations, many farms are likely to be operated less than optimally. Although some farmers may be over-fertilizing and over-liming, it is more likely that the converse is true. If they are applying less than the optimum quantities, the approach will still be valid. However, the estimated benefits in terms of crop yield would be underestimated since they should be greater than the fertilizer costs. If there is over-fertilization, the approach may overestimate benefits since additional deposits will not produce yield increases sufficient to warrant the increase in fertilizer that the deposition is assumed to displace.

Also, if the farmer is not amending his soils, overall crop yield may decline through acidification and the cost of the decline may be greater than the liming costs, hence there will be an underestimate of the damages. It should be noted that the changes in soil chemistry are partially reversible through soil management, and, although on an annual basis the farm may not be operated optimally, over the long term appropriate management may still be employed and the costs partially offset.

2. Availability of atmospheric nitrogen and sulphur

It is assumed that atmospherically deposited nutrients are direct substitutes for applied fertilizers, in terms of availability for uptake

by crops. Chemically this is true. However, the farmer is able to time fertilizer application with the growing cycle of his crops. Atmospheric deposition occurs year round and may not be as effective in stimulating plant growth on an annual basis. It is likely, therefore, that less applied fertilizer is required to replace atmospheric deposition. In this case, the benefits from atmospheric deposition would be overestimated.

3. One to one reaction of lime and hydrogen ions

Many of the arguments presented in Chapter 3, section 3.3.2 relating to the forestry model are applicable in this case. In general it is expected that this assumption will lead to an overestimate of damage costs.

4. Supply of nutrients

It is assumed that the annual atmospheric load of nitrogen and sulphur is less than the total annual requirements of the crops grown. This is likely to be true for nitrogen. However in some locations an excess of sulphur may occur.

4.3.3 Foliar Response Model - Approach

The general approach to foliar response is basically the same as that used in the forestry section. Initially, each of the commercially grown

crops in Ontario, as reported by the Ministry of Agriculture and Food (1979 and 1981) were assigned to one of the eight relative sensitivity groups cited earlier.

The assignments were made on the basis of yield changes in the marketable portions; accordingly the groupings do not reflect taxonomic relationships. For example, rutabagas and cabbage are both members of the genus Brassica; however rutabagas are placed in the root crop category since the marketable portion is the root, and cabbage is in the col crops. Although both crops might respond comparably overall to foliar impacts, the net result in terms of economic value of the change could be substantially different. For instance, acid deposition might induce a reduction in leaf area but not affect the root portion of the plant. Both rutabagas and cabbage plants would perhaps respond the same; however for rutabagas, there would be no economic consequence whereas an economic loss would result in the cabbage crop.

The specific crops according to their sensitivity groups follow.

Root Crops	- beets, carrots, parsnips, radishes, rutabagas
Leaf Crops	- lettuce, celery, spinach, tobacco, asparagus
Cole Crops	- cabbage, cauliflower
Tuber Crop	- potato
Legumes	- green beans*, white beans, soybeans
Fruit	- apples, cherries, grapes, peaches, pears, plums, raspberries, strawberries, peppers

* Fresh Market Only (i.e. not sold for processing)

cucumbers*, tomatoes*

Bulbs - onions

Grains and

Forage Greens - wheat, oats, barley, fodder corn, sweet corn, green corn*, hay, mixed grains

The yield response data from various simulated acid deposition experiments (Lee et al., 1980; Evans et al., 1980; Irving & Miller, 1978; Jacobson, 1980) were used to derive a series of dose - response curves for as many species as was possible in each sensitivity group. These results were combined by the consultants to produce a representative curve relating percent change in normal yield to pH dose for each sensitivity group. (See the solid lines in figure 4.1. The broken lines in the figure show the variation in the assumed relationships that is considered if the Monte Carlo option is used.) As there was no information available about lethal limits resulting from the direct effects of acid deposition on plants, the zero yield intercepts were estimated. The slope generated by the rapid reductions in yields for root crops from pH 3.5 to 3.0 provided some basis on which to estimate the lethal limits for this group -- the line was extended linearly to the x-axis. This slope was applied to all other groups.

* Fresh Market Only (i.e not sold for processing)

Figure 4.1

Dose - Yield Response Curves: pH of Rainfall and Yield of Agricultural Crops

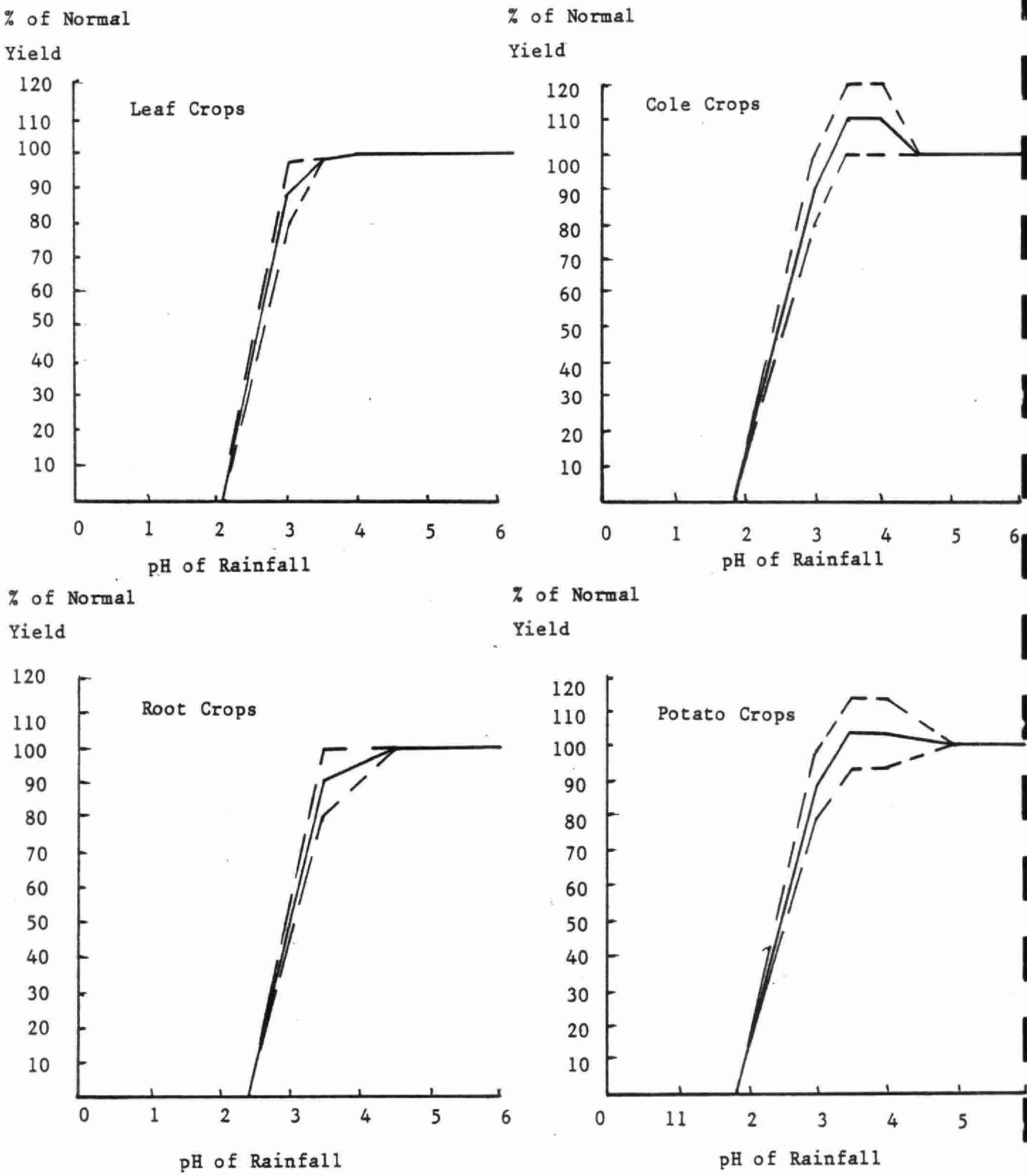
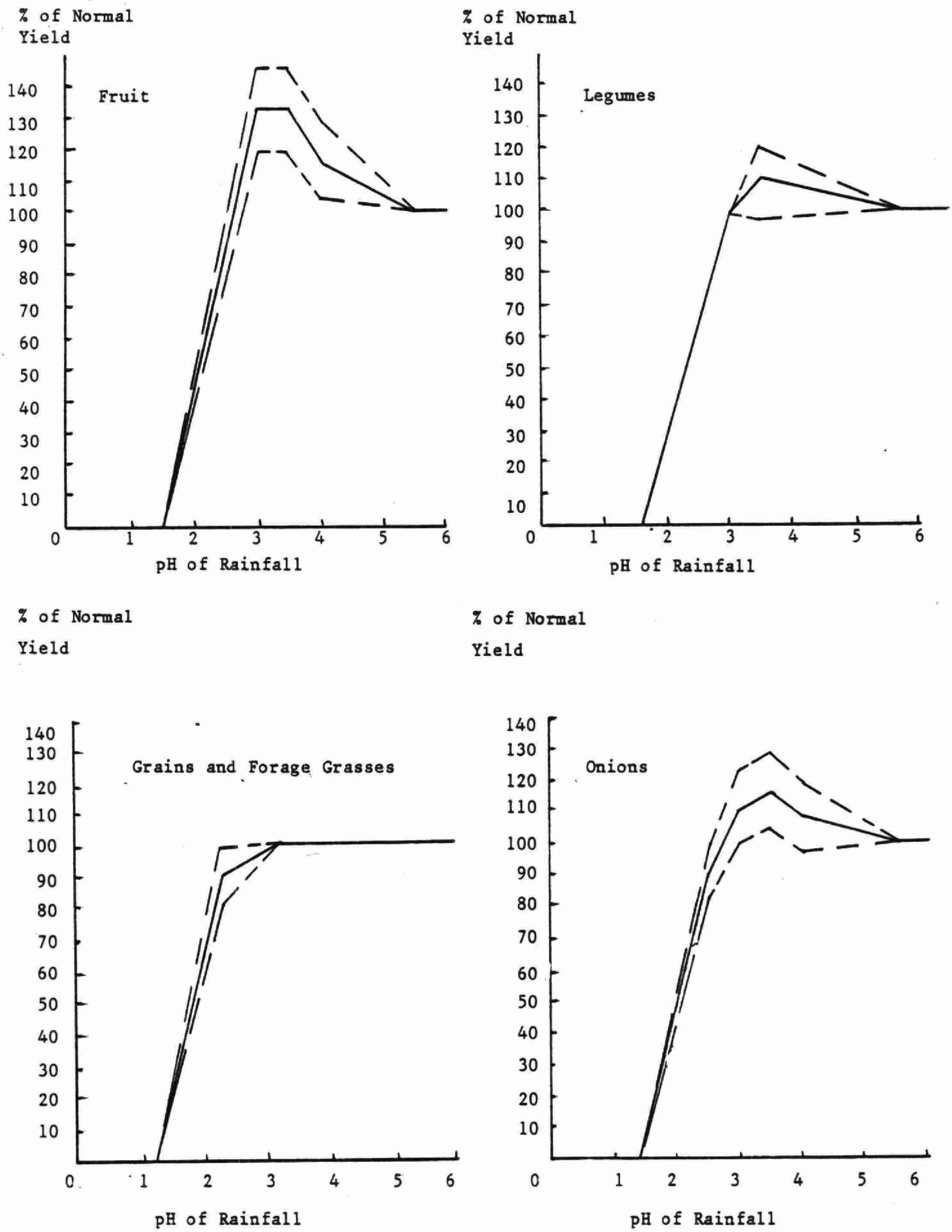


Figure 4-1 Continued

Dose - Yield Response Curves: pH of Rainfall and Yield of Agricultural Crops



4.3.4 Foliar Response Model - Assumptions and Limitations

1. pH is a weighted mean with respect to precipitation rate for the growing season, (i.e. hydrogren ion concentration multiplied by precipitation volume), and there may be wide variation around the mean. One extreme event in a season may be of greater significance for foliar damage than mean values.

2. Antecedent conditions (i.e. moisture availability, buildup of dry deposition, other environmental stresses such as ozone, disease, etc.) may be critical, and total volume of hydrogen ion of less significance. This factor is not incorporated into the model.

3. Dose - reponse data are based on simulated acid rain tests and not from direct observations in the field under ambient conditions. Confidence in the results is limited by the small number of species tested, by the experimental conditions employed (eg. methods of application, solutions used, frequencies of application, growing conditions) and by the lack of replication. The experimental design used to derive foliar damage results could lead to effects from soil modification in addition to direct impingement. Only recently has a generally accepted experimental procedure in terms of acid application and climatic and soil conditions been established (E. Piche, pers. comm.). Depending on climatic and soil conditions, effects could be over- or underestimated.

4. Dose-response data over the entire range are not available - zero yield or lethal limits had to be estimated. However, due to the relatively extreme pH values at which the lethal limit is reached with respect to ambient and projected acid loads, this limitation is not critical.

5. Crops may vary in their susceptibility depending upon specific site conditions. In addition, sensitivity is likely highly correlated to crop variety and the range of sensitivities between varieties may be as great or greater than between species. Crop variety changes according to region and individual farm operation; data constraints precluded consideration of these factors.

6. Different plant parts and growth stages may vary in their response to acid deposition. This is not accounted for. More specific data relating precise responses to specific loadings and probability distributions of rain pH for the growing season are required to incorporate this type of response pattern.

7. The model predicts yield reductions and assumes that changes in the value of the crop are directly proportional to yield. This will lead to a significant underestimate of damages for crops such as leaf crops where a small level of damage can greatly reduce marketability. Associated with this aspect is the need to determine whether the visible damage is to the marketed portion of the plant.

4.4 APPLICATION OF THE AGRICULTURE MODELS TO ONTARIO

The base case (wet) deposition rates of hydrogen ion, sulphur and nitrogen for 1979 in each of the 64 sub-regions considered in the study are reported in appendix A. Equations for estimating non-anthropogenic loadings are also provided. Owing to the uncertainty as to the magnitude of natural loadings, equations 4.1 - 4.3 provide more accurate estimates of changes in damages (or benefits) compared with the levels prevailing in 1979 than they do of the absolute levels of damages and savings. This is because all changes in acid deposition after 1979 may reasonably be attributed to anthropogenic sources.

Application of equations 4.1 - 4.3 to Ontario requires estimates of the land area supporting crop production in each region. Acreage on which leguminous (nitrogen fixing) crops were grown are excluded for estimating any savings in artificial nitrogen fertilization since the rate of fixation is partially a function of nitrogen availability. Changes in nitrogen supply may be compensated by a change in fixation rate and would therefore represent little change in benefit or cost.

Information on the 1979 production of 36 crops in each of Ontario's counties was obtained from staff of the Ontario Ministry of Agriculture and Food (OMAF) and published sources (OMAF, 1981). Using prorationing factors, developed by the study team and reviewed by OMAF, these production figures for counties were transformed to production figures for the 64 sub-regions of the province.

No official projections of crop production are available for Ontario. It was necessary, therefore, to make some reasonable estimates of future production so that the impact of acid deposition over time could be predicted. To accomplish this the following equations were used:

$$X_{i,1} = (2\ R_i + I_i)\ /3 \qquad (4.4)$$

$$X_{i,2} = (2\ R_i + I_i)\ /6 \qquad (4.5)$$

where: $X_{i,1}$ = projected average annual growth rate (%) for crop i, 1979-1990 (i=1..36)

$X_{i,2}$ = projected average annual growth rate (%) for crop i, 1991-2000.

R_i = average annual growth rate (%) for crop i, 1975-1979.

I_i = average annual growth rate (%) for crop i, 1971-1975.

The rationale for the form of these equations is to give greater weight to the more recent years in projecting future yields and to constrain growth (positive and negative) in the longer term (1991-2000) as limitations on the land become more pronounced.

The projections of crop yields derived from equations 4.4 and 4.5 are also used for estimating the direct foliar impacts of acid deposition using the relationships based on figure 4.1. All of the data referred to in this section are included in the data base provided by the

consultants as part of this study.

4.5 THE ECONOMIC VALUE OF THE IMPACT OF ACID DEPOSITION ON ONTARIO'S AGRICULTURE

Information on the cost of agricultural limestone, nitrogen and sulphur fertilizer to the farmer was obtained from the district offices of the Ministry of Agriculture & Food. A single average figure for each type of soil amendment was derived taking account of the quality differences among the soil amendments purchased. (The use of an average figure introduces an error factor insofar as soil amendment costs vary among regions.).

Table 4.1
Average Soil Amendment Costs in Ontario, (1980)

Soil Amendment	Cost/Tonne*
Agricultural Limestone (equivalent to 100% pure calcium carbonate)	30.4
Sulphur Fertilizer (equivalent to 100% sulphur)	964
Nitrogen Fertilizer (equivalent to 100% nitrogen)	730

* Includes material, transportation and application costs

Source: Based on information provided by the Ministry of Agriculture and Food.

Any change in the application of soil amendments will also involve a change in time spent by the farmer in those operations. The value of these increases or decreases in time is not included in the computational framework.

The economic value of the estimated damages from the direct foliar effects (see section 4.4.1) is calculated by multiplying the damages in crop production by the (1980) price of the crops. These prices were obtained from Agricultural Statistics for Ontario 1980. Regional variation in the prices paid is not accounted for, rather an average provincial price per crop is used. It is further assumed that any decline in crop production will have only an insignificant impact on harvesting costs and so no changes in harvesting costs are allowed for. (This will tend to overestimate the economic value of the reductions in crop production insofar as reduced production entails reduced harvesting costs.)

Chapter 5

COMMERCIAL FUR

CHAPTER SUMMARY

Little information exists as to the effects of acid deposition on commercial fur-bearing species. The approach taken in this study relates animal populations to forest productivity so that the estimated impacts of acid deposition on commercial fur harvests are derived from the estimated impacts on the forests.

5.1 INTRODUCTION

The effects of acidification on commercial fur-bearing species may occur via three mechanisms, all of which are linked ecologically. These include diminished availability of forage and cover, increased toxicity through mobilization of heavy metals, and disruption of micronutrient biochemical pathways. The Canadian Wildlife Service is currently conducting research on the impacts of heavy metals (i.e., lead, cadmium, and methylmercury) on populations of mink and muskrat in acidified areas (K. Fischer, personal communication; Anon, 1981) to determine:

- whether a correlation exists between contaminant concentrations in hair and other tissues;

- whether contaminant heavy metal levels might be correlated with different levels of acidification;

- whether reproduction might be impaired with increased heavy metal concentrations.

The Canadian Wildlife Service is also undertaking studies to determine whether excessive acid deposition is altering the micro elemental composition of herbivore browse, and whether selenium concentrations in the browse are being decreased sufficiently to promote selenium deficiency diseases in wildlife (K. Fischer, personal communication). As yet, no results are available from these studies, nor are there findings from any other experiments which suggest the types and significance of impacts of acid deposition on commercial fur-bearing species.

Theoretically, it is possible to postulate mechanisms in addition to the heavy metal toxicity. For example, species could be subdivided according to terrestrial and aquatic habitats and within each group characterized according to trophic level (i.e., herbivore and predator). Species falling in a given category could be expected to respond generally to acidification in a similar manner due to common changes in food availability, habitat quality, etc. To undertake this approach, however, rates of acidification of each of the basic habitat types would be required, which would have necessitated an excessive level of effort. In

addition, terrestrial species dominate the fur harvest in terms of economic return in virtually all sensitive areas in the province. In this regard, we are assuming that beaver (Castor canadensis) respond primarily to changes in the terrestrial environment since this species has proven to be tolerant of highly acidic aquatic habitats such as acid bogs. Therefore, the improvements offered by segregation of the response of fur bearers according to habitat, trophic state and species likely will not justify the effort required at the present time.

Instead, it was recognized that the majority of the fur harvest economic return is associated with species using terrestrial habitats and that the structure of the forest was a major determinant to overall fur bearer productivity. In addition, it is expected that there will be fairly good correlations between forest soils acidification and aquatic acidification in many parts of the province since the water chemistry of lakes is intimately related to watershed geochemistry. Accordingly, changes in aquatic furbearer populations will also be approximated by relating furbearer populations to forest productivity.

It is on the basis of this assumption that the approach to estimating the effects of acid deposition on commercial fur-bearing species has been derived.

5.2 Commercial Fur Yields and Forest Productivity

The solid line in Figure 5.1 shows an hypothesized relationship between

the percentage change in forest productivity and the percentage change in the sustainable yield of commercial furs.

Insofar as a relationship exists between forest productivity and fur-bearing species it is likely to be different for each species and each type of forest. Given the lack of data no allowance was made for this in the present study. Instead, an equation representing the relationship shown by the solid line in figure 5.1 (incorporating, at the user's discretion, uncertainty factors which allow the relationship to vary between the values shown by the dotted lines in figure 5.1) is used to derive the estimated impacts of acid deposition on commercial fur-bearing species.

The shape of the curve was derived according to the following considerations:

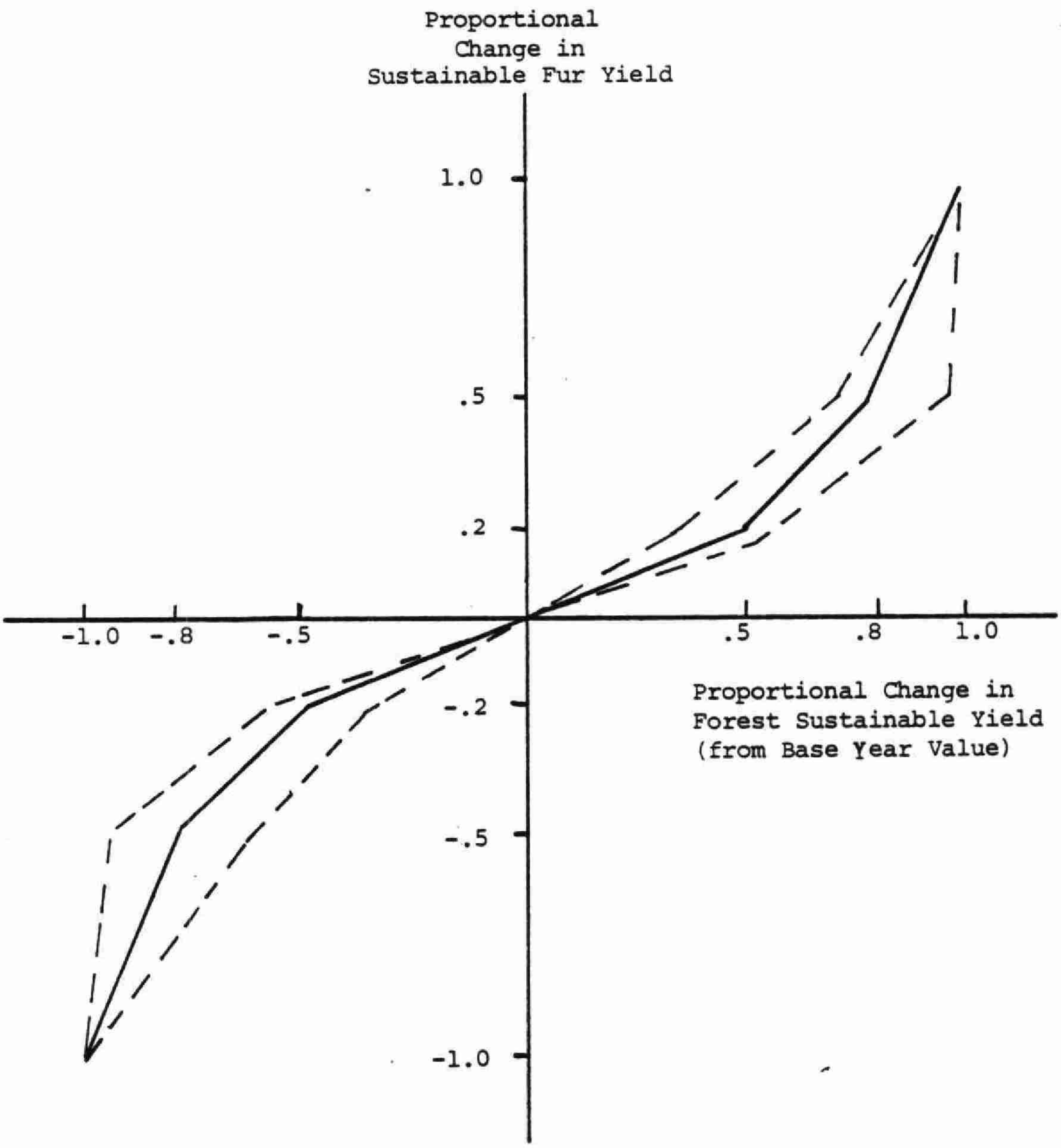
1. If there is no effect on the forests, then furbearers will likewise be unaffected; that is, the curve should pass through the origin.

2. If the forest is removed, that is, 100% reduction in yield, the furbearer populations will likewise disappear. Therefore, the curve should pass through the 1.0, 1.0 point.

3. At intermediate points on the graph, furbearers are considered to be less sensitive. This shape is based on observed fur yields from northern Ontario. Clear cutting and poor regeneration have resulted in a low productivity forest in some areas with respect to merchantable timber. However, fur yields are quite high, suggesting a direct one on one relationship between forest productivity and fur yield does not exist. Accordingly, furbearers are shown by the curve to be not as sensitive as forests to acidification in the early stages.

Figure 5.1

Assumed Relationship Between Forest Productivity
And Sustainable Commercial Fur Yield



The relationship between forest productivity and fur yield assumes that the major causative interaction is the alteration of habitat quality. Toxicity effects such as those being studied by the Canadian Wildlife Service could cause the response curve to become less convex/concave.

5.2.1 Estimating Impacts on Commercial Fur: Assumptions and Limitations

The approach to estimating losses in commercial fur due to anthropogenic inputs of mineral acids is subject to those limitations described for the forestry soils models (see Section 3.3.2). As well, there are shortcomings in assuming a direct relationship between loss in forest productivity and commercial fur harvest. For example, the assumption may hold reasonably well for some species which inhabit and depend almost exclusively on the forest ecosystem for food and protection (i.e., lynx, marten, fisher, etc.). However, for other species, including muskrat and otter, the relationship is tenuous, since such species are oriented almost exclusively to aquatic environments. Losses of these species would very much depend on the process of lake and stream acidification, and the various biochemical and physical interactions which occur in these environments. Many of these changes are likely closely correlated with forest responses at least according to the soil acidification model used in this study. In addition, most furbearing species are influenced in varying degrees by forest productivity for survival, indicating a general ecological validity for the basic assumption.

5.3 APPLICATION TO ONTARIO

Data for the 1979-1980 commercial fur harvests and quotas were obtained from the Ontario Ministry of Natural Resouces. As noted earlier for forestry, these data were available only by administrative district. Consequently, it was necessary to prorate the commercial fur data for

each administrative district to generate values for each of Hills' site districts. The prorating was based primarily on areal distribution, with some modifications where known variances existed.

Ideally, the economic value of losses in pelts should be determined for each commercial fur species. However, this would require values and projections for each of some 20 species. Accordingly, the economic value of a "typical" or "unit" commercial fur-bearing species in dollars is estimated by dividing the total revenues received from sales in 1979 by the total number of pelts sold. This is done for each site district. The total sales were derived from the 1979 Ontario Trappers Association auction in North Bay. The economic losses owing to mineral acid deposition are subsequently estimated by directly relating losses in forestry productivity to losses in productivity of commercial fur-bearing species and multiplying by the site-district specific unit species value. (No allowance is made for any change in harvesting costs in this estimate of economic effects, a factor which could overstate the economic value of any impacts.)

To estimate the losses of commercial fur harvest over time, it is necessary to project the annual harvest for each year for the duration of the period under study: 1980-2001. This is accomplished by assuming a uniform annual rate of growth (or decline) between the site district harvest of 1979-2000 and the targets established by the Ontario Ministry of Natural Resources for 2000 (prorated to each site district using the same approach described above for prorating the 1979-1980 harvest).

It should be noted that the number of beaver harvested in 1979-1980 was less than the number of pelts which could have been taken had trappers harvested their lines to realize quotas set by the Ministry of Natural Resources. Quotas or sustainable yields exist only for beaver; these are based on the premise that each active lodge will yield an average of 1.5 beaver per year. The quotas are set as 75% of the total potential harvest in a trapline. For example, if 100 beaver are estimated for a trapline, the trapper must harvest 75 pelts in order to retain the line. For 1979-1980, 247,317 beaver could have been harvested according to quotas established by wildlife managers; however, only 209,135 animals were taken. The difference (38,182 animals) could be important for estimating the economic value of acid deposition impacts. For example, if it is found that beaver populations are reduced by x per cent owing to atmospheric loadings of mineral acids, but that quotas continue to go unharvested owing to insufficient trapper effort, a real economic loss might not occur. A real economic loss would be experienced if the entire beaver quota was being harvested at or near its sustainable yield, and if mineral acid deposition was negatively affecting a component of that sustainable yield. According to the current structure of the model all currently estimated changes in sustainable fur harvests are assumed to correspond to equivalent proportional changes in the actual harvest.

Approaches for determining quotas for fine fur species are not generally available throughout much of Ontario, although ways and means of establishing quotas are under investigation. Wildlife mangers generally

are of the view that species other than beaver are currently being harvested at their level of sustainable yield and so the approach taken in this study to estimating the economic value of changes in commercial fur harvests seems reasonable.

CHAPTER 6

COMMERCIAL FISHERIES

Chapter Summary

The effects of acid deposition on fisheries have received considerable attention from fisheries biologists. This chapter draws on that work and describes a biophysical model based on lake alkalinities and fish productivity for estimating lake acidification impacts on commercial fisheries. Data for applying the model to Ontario have been assembled and can be readily assessed by the computational framework.

6.1 INTRODUCTION

The issue of acid deposition and fisheries is highly complex. It involves the interaction of chemical, physical, and biological processes through a multiplicity of pathways and relationships. In order to gain an understanding of how commercial fish species respond to acidification, a number of problems must be addressed including:

(i) identification of lakes within Ontario which are sensitive to acid deposition;

(ii) quantification of acidification rates in relation to varying acid loads and biophysical, chemical and hydrologic characteristics of a lake and its watershed; and

(iii) clarification of responses of commercial fish species to acidification.

To address this problem for Ontario's inland sports fishery, the Federal Department of Fisheries and Oceans retained Hough, Stansbury + Michalski in collaboration with J.E. Hanna Associates Inc. in December of 1980. Specifically, the Department mandated the consultants to design, assess and apply a methodology which would determine qualitatively and quantitatively those sports fish communities in inland Ontario waters which are vulnerable to loadings of mineral acids, their current productivity, and their potential rate of change under varying atmospheric acid loading rates. As a point of departure for the assignment, the consultants reviewed a number of existing approaches to analyzing the effects of acidification on lakes and fisheries (see Hough, Stansbury + Michalski and J.E. Hanna Associates, 1981), and concluded that each suffered from one or more limitations. Accordingly, a decision was made to develop a methodology which would determine rates of acidification by estimating each alkalinity contribution to a lake system and how an acid load would affect this supply; this aspect of the model was termed the physical/chemical component. The predicted chemical changes could then be related to changes in the fish yield through alterations occurring in a lake's alkalinity concentration; this was the biological component. The basic premise with the model is that as alkalinity is depleted by acidification, the long term sustainable yield loss of fisheries can be predicted. Details on both components are presented in the following pages.

Because the physical/chemical component of the model is applicable to the present study, The Ont. Min. of the Env. approached Dr. J. Cooley,

Acid Rain Program Manager for the Department of Fisheries and Oceans and requested and received permission to use the methodology for estimating commercial fishery losses in inland Ontario lakes. Accordingly, many of the technical details which follow on the physical/chemical component have been reproduced from a report entitled "An Approach to Assessing the Effects of Acid Rain on Ontario's Inland Sports Fisheries". (Hough, Stansbury & Michalski and J. E. Hanna and Associates, 1982). Considerable modifications to the biological component of the model are specific to this assignment; these are explained fully in subsequent pages.

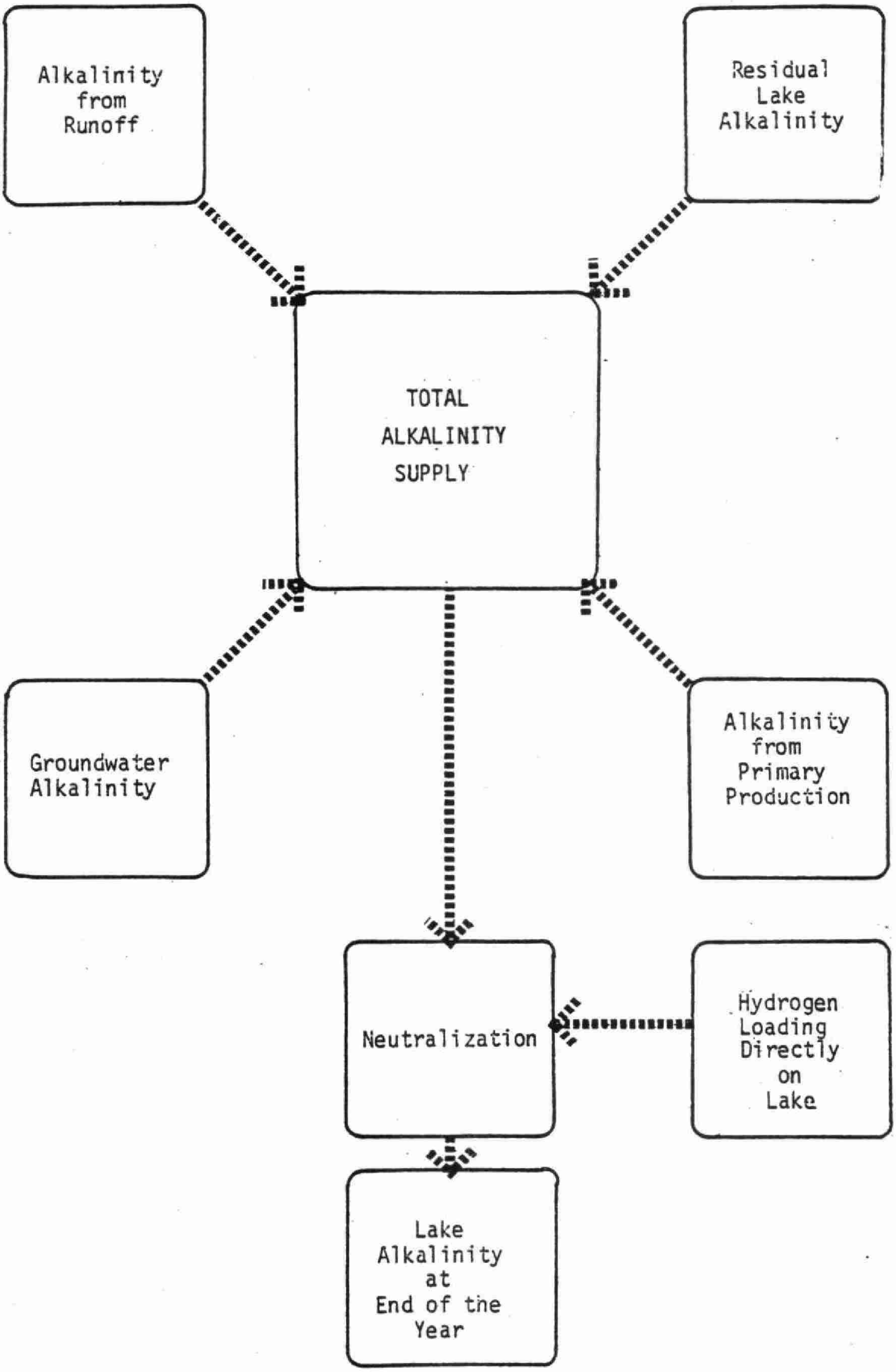
6.2 COMMERCIAL FISHERIES AND THE EFFECTS OF ACID DEPOSITION: BACKGROUND

Following is presented an overview of the basic concept of the acidification model for both the physical/chemical and the biological aspects.

6.2.1 Physical/Chemical Model Concept

The approach is based on an annual alkalinity or acid neutralizing capacity (ANC) budget for a lake/watershed system. The ANC sources include overland runoff, groundwater, autochthonous matter, and residual lake alkalinity (Figure 6.1). Hydrogen ion input from the atmosphere is balanced against the store of ANCs on an annual basis, and resultant lake ANCs are predicted after each year's loading. In this work, ANC and hydrogen ion load were mixed using equivalent measures, and the net

Figure 6.1



Schematic of alkalinity budget concept.

result was converted to a concentration and lake pH by including a hydrologic budget for each system. The concept of the model is similar in several aspects to the widely used phosphorus budget model of Dillon and Rigler (1975).

The concept is based on a complete mixing, single discharge hydrologic regime to predict ANC. At the start of each annual cycle, all inputs, including the water and ANC in the lake, are accumulated in one large hypothetical beaker. At the end of the year, all outputs are released (i.e., evaporation loss and lake outflow), leaving the original volume of the lake.

6.2.2 Biological Model Concept

The biological model has two components; one estimates long term clinal or pre-lethal effects while the second focusses on critical threshold responses. The first component is based on the findings of Ryder (1965) in developing the morphoedaphic index (MEI). His analysis demonstrated that total dissolved solids (TDS) was a significant variable in determining fish yield. As alkalinity accounts for most of the TDS in many natural unacidified waters, substitution of alkalinity for TDS in the MEI equation with appropriate modifications, yields an equation with almost the same precision as that of the original MEI. In this regard, Ryder's calculations have indicated that the r value decreases from 0.85 (with TDS in the MEI equation) to 0.82 (with alkalinity substituted for TDS in the MEI equation), using the original data base. As indicated

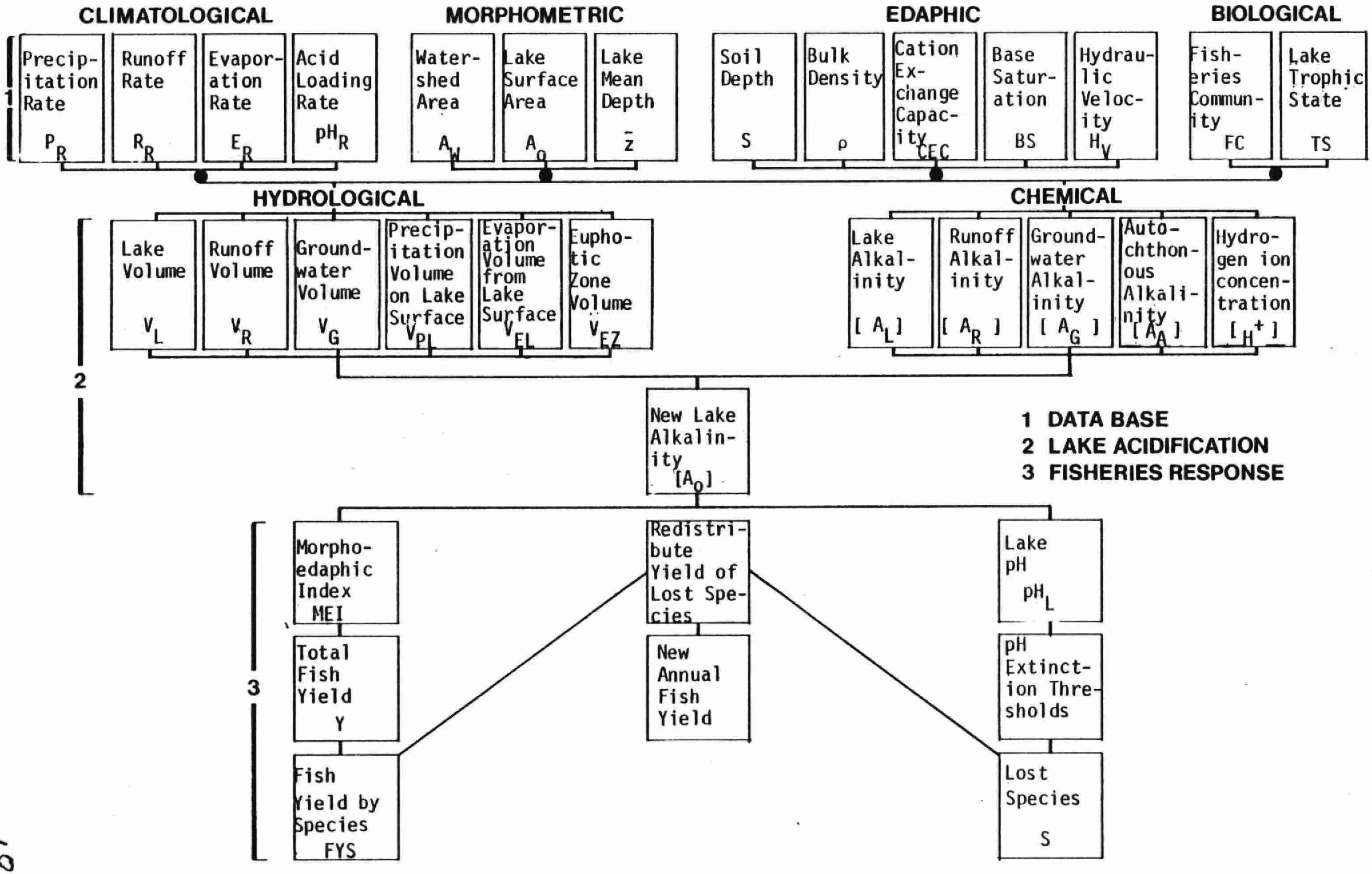
earlier, the premise is that as alkalinity is depleted by acidification, the long term sustainable yield of a water body will also decline. By substituting the predicted changes in alkalinity generated by the physical/chemical model, changes in sustainable yield can be predicted.

The second biological component is activated once the predicted lake pH's fall below certain critical thresholds, which vary for each commercial fish species. When a threshold pH is reached for a given species, it will disappear from that community. The biological energy flow utilized by that species will be partially distributed amongst those fish species and other aquatic organisms which continue to survive. As each successive threshold is reached, the commercial fish community is depleted of species, and a redistribution of productivity occurs until the last fish species is removed; at this point, the lake is termed "extinct"; extinct lakes are those no longer capable of game fish production, although overall primary and secondary production may still be relatively high. The MEI predictions continue throughout the threshold phase as a means of measuring the productivity to be redistributed. The overall concept is presented schematically in Figure 6.2.

6.3 DETAILS OF THE METHODOLOGY

In this section, the analytical procedures for the physical/chemical and biological response model are described; specific comments relating to each step of the process are provided.

Figure 6.2 Analytical framework for estimating impacts of acid deposition on inland fisheries.



6.3.1 Physical/Chemical Model Formulation

The basic formulation of the lake/watershed rate of change model is expressed by the following equation:

$$[A_L{}^1] = \frac{[A_L{}^o]V_L + [A_R]V_R + [A_G]V_G - [H^+p]Ao + [A_A]V_L}{V_L + V_R + V_G + V_{PL} - V_{eL}} \qquad (6.1)$$

where:

$[A_L{}^1]$ is the alkalinity (meq/l) of the lake at the end of one year of acid loading;

$[A_L{}^o]$ is the alkalinity in the lake (meq/l) at the beginning of the year;

V_L is the volume of the lake (litres);

$[A_R]$ is the alkalinity of the surface runoff (meq/l);

V_R is the annual runoff volume (litres);

$[A_G]$ is the alkalinity of the groundwater (meq/l);

V_G is the volume of the groundwater (litres);

$[H^+p]$ is the hydrogen ion concentration of rainfall (meq/m^2);

A_o is the surface area of the lake (hectares);

$[A_A]$ is the alkalinity generated by biological processes in the lake (meq/l);

V_{pL} is the volume of precipitation landing directly on the lake (litres);

V_{eL} is the evaporation loss from the lake's surface (litres).

Each of the components of the formula is derived according to the following procedures.

a) $[A_L o]$, the current lake alkalinity, is equal to A_L° in the year preceding, except in the first year. It is derived in the following manner. First, consider a lake with pure water and 0 alkalinity which is receiving water from runoff, rainfall, and groundwater, each of which has a certain alkalinity. After a number of years, the lake will reach an equilibrium concentration which reflects the relative contribution from the various sources. This alkalinity can be calculated according to the following steps.

In year 1,

$$[{}^1A_{Lo}] = \frac{[{}^oA_L{}^o]V_L + [A_R]V_R + [A_G]V_G - [H^+p]Ao + [A_A]V_L}{V_L + V_R + V_G + V_{PL} - V_{eL}} \tag{6.2}$$

Since,

$[{}^oA_L{}^o] = 0$, the first term of the equation is 0 and can be ignored in the first year.

At equilibrium, the alkalinity in successive years is equal. Therefore,

$$[{}^{n+1}A_L{}^o] = [{}^nA_L{}^o] \tag{6.3}$$

substituting in equation (6.2)

(6.4)

$$[^{n+1}A_{Lo}] = \frac{[^{n+1}A_L{}^o]V_L + [A_R]V_R + [A_G]V_G - [H^+p]Ao + [A_A]V_L}{V_L + V_R + V_G + V_{PL} - V_{eL}}$$

rearranging and simplifying results in

$$[A_L{}^o] = \frac{[A_R]V_R + [A_G]V_G - [H^+p]Ao + [A_A]V_L}{V_L + V_R + V_G + V_{PL} - V_{eL}} \tag{6.5}$$

Each of the input values in this equation can be derived using the initial input data.

b) V_L, the lake volume, is the product of z, the mean depth of a lake (metres), and A_o, the surface area of the lake (hectares). The equation for lake volume is

$$V_L = A_0 \times z \times 10^7 \tag{6.6}$$

Mean depths were available for some lakes through the OFIS data base; estimates for the remainder were interpolated by the consultants and refined by fisheries managers of the Ministry of Natural Resources.

c) $[A_R]$, the alkalinity of runoff, is a function of both the physical and chemical composition of the surficial geology, including the cation exchange capacity (CEC) and base saturation (BS) of soils. The calculation is designed to predict only the response of aluminosilicate minerals subjected to acidic deposition. In this reaction, hydrogen ions displace basic cations such as calcium and magnesium, resulting in buffering or hydrogen uptake. The extent of this reaction is determined in part by the CEC of the mineral, which is defined as the total amount of exchangeable cations (metallic as well as hydrogen) which are adsorbed on the mineral (Malmer, 1976). As reported by Harvey et al. (1981), "...the CECs vary significantly with various soil components (Bolt and Bruggewert, 1978) (e.g., 2-80 ueq/gram for kaolnite; 150 ueq/gram for illite; 800 ueq/gram for monmorillonite and 2,000-3,000 ueq/gram for humus). Since the CEC varies with the material and also with the number of reactive sites available, such factors as grain size or specific area may alter values for this component."

BS, the base saturation is defined as the fraction of all CEC sites occupied by basic cations as opposed to acidic H^+ ions. As the BS decreases, so does the alkalinity in the runoff. BS and CEC values for watersheds were determined by reviewing various large scale surficial geomorphology maps and applying published values to watershed units selected for the study.

In order to calculate $[A_R]$, the change in BS of the soils with acid loading is estimated according to the following equations.

$$BS^{\circ} = \frac{(A_W)\ (S)\ (p)\ (CEC)\ (BS^{o})\ (10^6) - [H^+{}_p]A_W\ (10^4)}{(A_W)\ (S)\ (p)\ (CEC)\ (10^6)} \qquad (6.7)$$

where,

BS° is the base saturation of the soils (as a dimensionless fraction) after one year of acid loading;

A_W is the land area of the watershed (hectares);

S is the depth (cm) of the active soil layer;

p is the bulk density of the soil (gm/cm^3);

CEC is the cation exchange capacity (meq/100gram) of the soil;

BS^{o} is the base saturation of the soil (as a dimensionless fraction) at the beginning of the year, which is a function of past acid loading;

$[H^+{}_p]$ is the hydrogen ion concentration of the rainfall (meq/m^2).

The new BS which is calculated from equation (6.7) can then be converted to a pH runoff (pH_R) by using a revision of the original equation of Kramer et al. (1979) .

$$pH_R = (3.03)\ (BS^{\circ}) + 4.55 \qquad (6.8)$$

By assuming an equilibrium between dissolved and atmospheric

concentrations of CO_2, and a reaction temperature of 25°C, pH_R can be converted to alkalinity (meq/l) using,

$$\log [A_R] = pH_R - pK - pP_{CO2} \tag{6.9}$$

where,

pK is the negative logarithm constant for the bicarbonate system and at 25°C is equal to 7.82; and

P_{CO2} is the negative logarithm of the partial pressure of CO_2 at 25°C, which is equal to 3.0.

d) V_R, the annual runoff volume, is dependent on the value of precipitation, evapotranspiration and infiltration rates, topography, surface area of the watershed, etc. Runoff values provided by Pentland (1968) were used with the equation,

$$V_R = R_R \times A_W \times 10^5 \tag{6.10}$$

where,

R_R is the runoff rate (cm/year); and

A_W is equal to the area of the watershed (hectares).

e) $[A_G]$, the groundwater alkalinity, is generally less variable over time than $[A_R]$, due to its long retention time before discharge, the high P_{CO2} in groundwater, and the large available contact surface in the ground. However, $[A_G]$ does vary with depth. For

purposes of this study, a constant value for shallow to moderate depth groundwater aquifers of 2 meq/1 $CaCO_3$ was used (Wang and Chen, 1978).

f) V_G, the annual groundwater inflow, varies according to the permeability and depth of the watershed overburden, the location of the lake in the watershed, the mean depth of the lake, orientation and contact length of the lakebed with aquifers, the hydraulic gradient, the depth of the groundwater table, and a variety of site specific factors. V_G can be calculated using Darcy's equation; however, it was not feasible to collect site specific information for the above factors sufficient to apply this formulation directly. Therefore, Darcy's equation was modified according to a lake's position in the watershed and rainfall rate to approximate V_G as follows:

$$V_G = (z)\ (A_o)\ (H_V)\ 10^{(.6-Ao/Aw)}\ (P_R/80)\ (3.1536)\ (10^{10}) \qquad (6.11)$$

where,

V_G is the annual volume of groundwater flowing into the lake (litres);

z is mean depth of the lake (metres);

A_o is the surface area of the lake (hectares);

A_W is the watershed area of the lake (hectares);

H_V is the mean hydraulic velocity of the soils in the watershed (cm/sec); and

P_R is the precipitation rate available from various meteorological records (cm/year).

g) $[H^+{}_p]$, the hydrogen ion content of the rainfall (meq/m^2), varies between events and within events (Hales, 1981); it also varies spatially according to proximity to emission sources, prevailing winds, and a variety of related atmospheric parameters (Murray, 1981). Acid-causing substances, in particular sulphates, can also be deposited as dry particulates and aerosols (Barrie, 1981). (See Appendix A.)

h) V_{PL}, the annual rainfall volume landing on the lake (litres), and is the product of P_R (cm) and A_O (hectares). As noted above, P_R is available from meteorological records; V_{PL} can be calculated as follows.

$$V_{PL} = (P_R)\ (A_O)\ (10^5) \qquad (6.12)$$

where,

V_{PL} is the annual rainfall volume input directly to the lake (litres);

P_R is the annual precipitation rate (cm); and

A_O is the surface area of the lake (hectares).

i) $[A_A]$, the internal generation of alkalinity from primary production, is a critical factor in the acid-base balance of lakes.

Dr. P. Dillon of the Ministry of the Environment's Limnology and Toxicity Section indicated that this source might be maintaining buffering capacity in a number of acid sensitive lakes in the Parry Sound, Muskoka, Haliburton Highlands area of the province; this source could be sufficient to keep these lakes buffered for many years, assuming that current inputs of mineral acids do not escalate. The effect of primary production is to utilize NO_3^- and H^+, with a resulting increase in alkalinity and pH in surface waters, according to the following basic stoicheiometric equation (Redfield et al., 1963).

$$106CO_2 + 16NO_3^- + HPO_4^{2-} + 122H_2O + 18H^+ \; C_{106}H_{263}O_{110}N_{16}P_1 + 138O_2 \qquad \underline{(6.12^1)}$$

This has been inferred by Zimmerman and Harvey (1979) in Crosson Lake, Haliburton. In 1978, the pH in the lake rose from about 5.1 in May to 6.6 by August. While no measurements of primary production were made, $[NO_3^-]$ decreased from 15.0 uM to 1.0 uM, indicating that nitrate uptake during photosynthesis may have consumed about 14 meqH$^+$/l, sufficient to account for the observed rise in pH of the epilimnion.

On the other hand, ammonium ions (NH_4^+) entering a lake via atmospheric deposition may be taken up by plants with a corresponding H^+ release. However, in Crosson Lake, $[NH_4^+]$ varied between 0.3 uM and 0.5 uM during the May to August period, suggesting that an ammonia driven photosynthetic reaction was not

likely operating.

While acknowledging that very little information is available on alkalinity derived from photosynthesis, sufficient evidence exists which suggests the need to incorporate an estimate of buffer generated from autochthonous matter into the alkalinity budget. Values were determined from a review of annual estimates of primary production (Fee, 1980; Johnson et al., 1970; Michalski et al., 1973) for Ontario's Precambrian Shield lakes. The estimates were selected to reflect production in a variety of fish community type lakes (see Section 6.3.2), and were converted to meq/l/year and further adjusted to reflect net rather than gross alkalinity gain in a lake (see Table 6.1 for estimates for each fish community). As indicated, the values range between 0.024 meq/l/year and 0.126 meq/l/year, which are of the same order of magnitude as those reported by the Ministry of the Environment's Limnology and Toxicity Section for unproductive lakes (i.e., 0.010 meq/l/year to 0.015 meq/l/year) (P.J. Dillon, personal communication).

j) V_{eL}, the volume of water (litres) lost through evaporation from the lake surface, is a function of the temperature of lake and atmosphere. Estimates of losses owing to evaporation are available from Pentland (1968), and are calculated using:

TABLE 6.1

ESTIMATES OF NET ALKALINITY (MEQ/L/YEAR)
GENERATED FROM PHOTOSYNTHESIS FOR NINE
COMMERCIAL FISH COMMUNITY CATEGORIES

Fish Community	Primary Production g/cm^3/year	Alkalinity Generated from Primary Production (meq/l/year)
Lake whitefish	8	0.094
Lake whitefish and yellow pickerel	8	0.094
Lake trout and lake whitefish	2	0.024
Lake trout, lake whitefish and yellow pickerel	5	0.059
Lake trout, lake whitefish and northern pike	5	0.059
Lake trout, lake whitefish, northern pike and yellow pickerel	8	0.094
Northern pike and yellow pickerel	15	0.126
Lake whitefish, yellow pickerel and northern pike	12	0.100
Lake whitefish and northern pike	8	0.094

See Section 6.3.2 for derivation of fish community lakes.

TABLE 6.2

THRESHOLD pH CUT-OFF POINTS FOR SPECIES OF FISH HARVESTED COMMERCIALLY FROM INLAND ONTARIO LAKES, 1979

Fish Species	pH	Effects	References
Lake whitefish and lake herring	5.5		Authors' best estimate based on communication with staff of Ministry of Environment's Limnology and Toxicity Section
Yellow pickerel,	5.5	Found absent at a pH of 5.2 - 5.8	(i) Beamish, 1975 and 1976
Northern pike	4.7	Relatively tolerant, with reproduction and hatchability of eggs seriously impaired at pH 4.5 - 5.0	(i) Beamish, 1975 and 1976 (ii) Beamish and Harvey, 1972 (iii) Vallin, 1953 and 1962
Sucker, chub	5.0		Authors' best estimate based on communication with staff of Ministry of Environment's Limnology and Toxicity Section
Burbot	4.5		"
Lake trout	5.5	At pH of 5.5 and below, lake trout reproduction fails and below a pH of 4.7, populations cannot be maintained	(i) Beamish *et al*, 1976
Rock bass, crappie and white bass	5.7	Below pH of 5.5 - 6.0, reproduction success fails	(i) Beamish, 1975 and 1976 (ii) Lewis and Peters, 1976
Sturgeon	5.0		Author's best estimate based on communication with staff of Ministry of Environment's Limnology and Toxicity Section
Yellow Perch and sauger	5.5	Found absent at a pH of 5.2 - 5.8	(i) Beamish, 1975 and 1976
Bullhead	4.2		Authors' best estimate based on communication with staff of Ministry of Environment's Limnology and Toxicity Section

$$V_{eL} = (E_R)\ (A_o)\ (10^5) \tag{6.13}$$

where,

V_{eL} is the lost volume of water from the lake surface from evaporation (litres);

E_R is evaporation rate (cm/year) from Bruce and Weisman (1966); and

A_O is the surface area of the lake (hectares).

Equation 6.5 is calculated and the predicted alkalinity is compared to measured values for the lake. The difference is then inserted into equation 6.5 as a constant for that lake. This factor accounts for alkalinity contributed from soil erosion and subsequent solution of carbonate material within a lake's watershed and/or chemical solution of carbonates from exposed bedrock. Where these sources of alkalinity are available, the supply is extensive, and is essentially unaffected by acid deposition. Equation 6.1 is calculated for a number of cycles by substituting the predicted $[A_L^{\circ}]$ for the initial $[A_L^{o}]$ in the subsequent run. In this way, an acidification/time curve can be constructed. The model can be run for a fixed period of time (i.e. 20 years), or until a critical pH is reached (i.e. pH of 5.5). Also by varying the $[H^+p]$ term, the effects of various acid loading scenarios on lake alkalinity can be predicted.

6.3.2 Biological Responses

Most research on acidification of Ontario Shield lakes has focussed on the critical or threshold pH in which a fish community is no longer viable (Beamish, 1974). When the buffering capacity of a lake has been eliminated and the summer pH drops below about 5.5, fish populations decline rapidly (Mulvaney and Hadden, 1981); fish cannot survive for long below a pH of 4.5 (Beamish, 1976). As reported by Harvey et al., 1981, "...The growth of fish has been observed to decrease, increase, stay the same or change mid-life, presumably under the combined effects of metabolic stress and reduced competition for food....In Scandinavia, one of the earliest indicators of lake acidification was a change in the size and growth rate of fishes. Almer (1972a) recorded Swedish observations of the 1930's on increased growth of the roach (Leuciscus rutilus) in Hogsjon, presumably resulting from a reduction in roach population size. Almer et al, (1974) confirmed these results on roach in lakes of pH 4.6-5.5. Almer (1972b) reported that the perch (Perca fluviatilis) in Stora Holmevatten experienced an increase in size before extinction. This change in perch growth with declining pH has now been reported for numerous lakes. Jensen and Snekvik (1972) recorded a sequence of changes from the 1930's in the populations of brown trout in the rivers and lakes of the Sorlandet region of southern Norway: (i) over-population of small, slow-growing trout; (ii) reduction of population in size; (iii) increased growth; (iv) recruitment failure; (v) survival of a few

large trout; and (vi) complete elimination of trout."

Changes in productivity during the lake acidification phenomenon prior to the threshold pH being approached have received little investigation. However, fisheries managers have been estimating the maximum amount of fish biomass which can be produced in a given period of time by considering such factors as water chemistry, total water surface area, mean depth, and climate. The predicted value is usually expressed as a theoretical limit, and a number of influencing factors such as availability of suitable habitat, spawning areas, species composition, and harvest pressure may cause permanent or temporary restrictions to realizing the full potential yield. In Ontario and other parts of Canada, fisheries managers have been using the morphoedaphic index (MEI) (Ryder, 1965 and Ryder et al., 1974) to estimate natural fish production or annual sustainable yield. The equation for the MEI is as follows:

$$MEI = \frac{TDS}{\bar{z}} \qquad (6.14)$$

where,

TDS is the concentration of total dissolved solids in the lake water (mg/l); and

$\bar{z}$ is the mean depth of the water body (metres).

Ryder related known morphoedaphic index values to recorded long term commercial fish harvest data; the resulting equations

provided an estimate of a lake's long term sustainable yield of fish. The value is defined as the number of fish which can be harvested without causing a long term decrease in subsequent years. The index is a conservative yield estimator and should be considered as a first approximation when other fisheries information is not available. In some cases, fish yield estimates derived using the MEI may be too liberal, especially in northern climates where nutrients and energy resources are limited. On the other hand, a few lakes have been overharvested for years according to MEI predictions, of sustainable yields, yet they continue to sustain healthy, productive fish populations (Adams and Olver, 1977). Although harvesting within a range of one-half to twice the estimated sustainable yield has been safely carried out in some lakes (Ryder, 1979), and this has been allowed for in the computerized framework when the Monte Carlo option is selected, the Ministry of Natural Resources believes that for many lakes, the estimated sustainable yield should be applied rigorously, at least until more convincing data become available suggesting that variation from the estimated sustainable yield can occur without undermining the fishery. While Ryder's technique has its limitations, this method remains the most useful and accepted predictive quantitative tool available to fisheries managers.

The MEI can be converted to yield by the following equation:

$$y = 1.378\ (MEI)^{0.4461} \qquad (6.15)$$

where,

y is the annual areal yield (kg/ha/year);

The total yield of a lake can be determined from:

$$Y = y\ (A_O) \qquad (6.16)$$

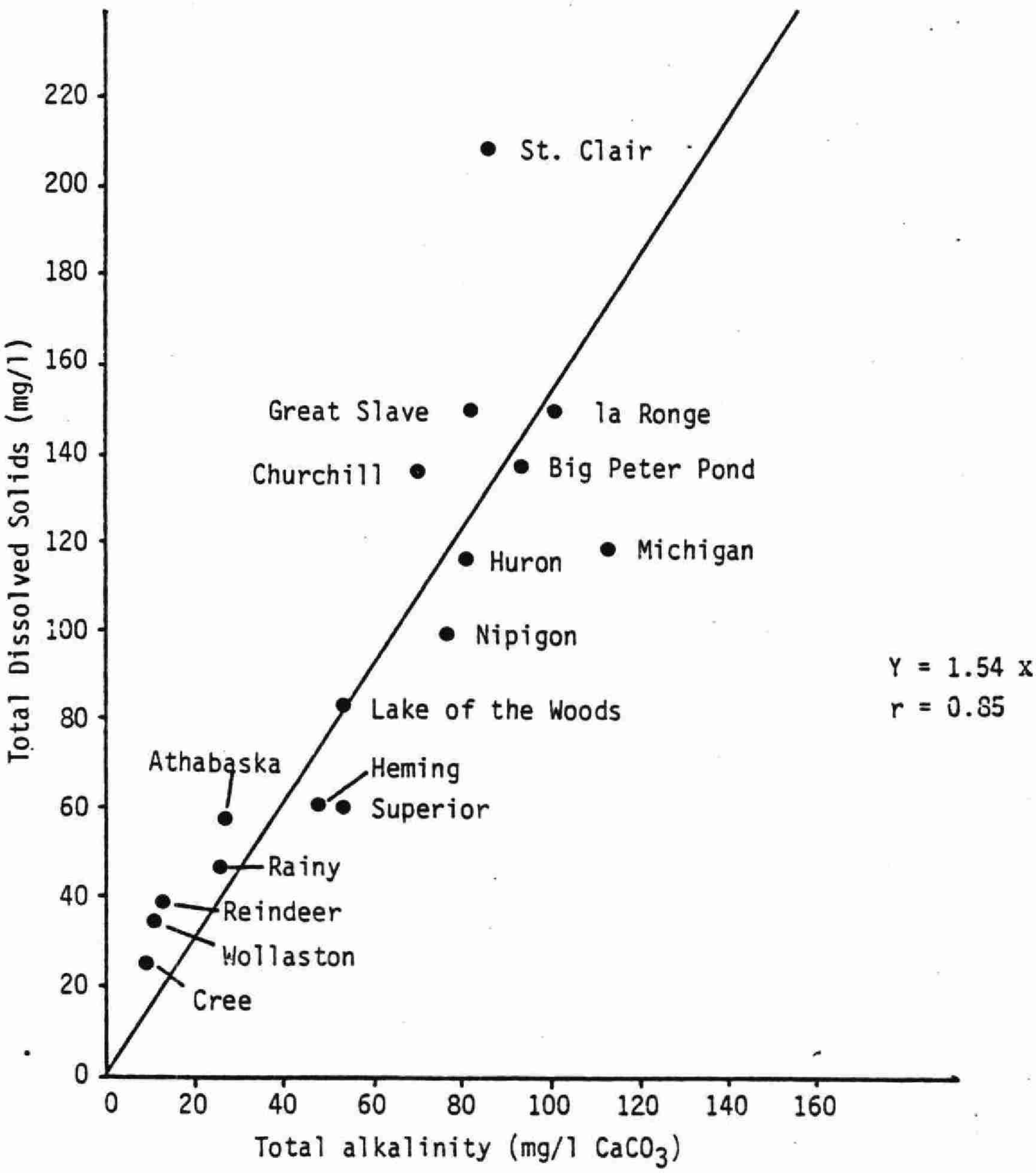
where,

Y is the annual sustainable yield for a given lake for all fish species (kg/year).

A_O is the surface area of the lake (hectares).

In most natural waters, bicarbonates account for a significant amount of the total dissolved solids content (Figure 6.3). By substituting alkalinity in the MEI equation for total dissolved solids, fish yields can be calculated as acidification proceeds, since the acidification process reduces alkalinity. The equation for the MEI then becomes:

Figure 6.3



Relationship between measured values of total dissolved solids (mg/l) and total alkalinity (mg/l as $CaCO_3$) in sixteen lakes. Data were reproduced from Ryder (1965) and other scientific publications.

$$MEI_A = \frac{1.54\ [A_L]}{\bar{z}}$$

where,

MEI_A is the morphoedephic index in which alkalinity has been substituted for total dissolved solids and,

$[A_L]$ is the predicted alkalinity of the lake at the end of one year, expressed as mg/l $CaCO_3$.

z is the mean depth of the water body (metres).

As indicated above, the estimation for total annual sustainable yield includes all species of fish. In order to assign a proportion of a lake's total sustainable yield to that component of the fishery which is harvested commercially, lakes were categorized according to 15 fish community types using harvest records from 106 lakes fished commercially in 1979. These categories, together with the proportion of each lake type's sustainable yield which can be assigned to commercially harvested species are presented in Appendix B. It is worth repeating that the percentage values are based on a single year's recorded harvest, and not on long-term catches averaged over the period of catch.

The physical/chemical/biological methodology to this point predicts long-term trends in acidification and subsequent losses in fish yield. Throughout the decline in alkalinity, the pH is predicted based on equation 6.9, and is monitored in relation to the reported critical threshold values for the various species in a lake. As soon as a critical threshold is reached for a particular species,

it disappears from the community. In Table 6.2, the threshold pH levels for commercial fish species are presented together with reference sources.

Finally, it is necessary to take into account the extent to which a lake's total annual sustainable yield would change as the first species is lost, then the second species, and so on. For example, if lake trout is the first species lost from a community, to what extent would the remaining species expand into the functional gap created? A decline in the total productivity of a lake is likely to be accompanied by a change in the species composition. Possibly, those species most susceptible to increased acidity will show a positive, if temporary, increase in productivity as lake acidity increases. This type of phenomenon has been observed in the La Cloche Mountain Lakes, where yellow perch (*Perca flavescens*) and rock bass (*Amblophites rupestris*) populations were noted to increase substantially after lake trout were lost from the fishery (Ryan, 1976). The detailed assumptions used in this study to account for these effects are given in Appendix B.

6.4 ASSUMPTIONS AND LIMITATIONS OF LAKE/ACIDIFICATION/FISHERIES RESPONSE MODEL

Arguments will be made that insufficient knowledge is available concerning alkalinity sources, hydrogen cycles, and related chemical and physical reactions to apply the model and that its use is premature. While acknowledging that the methodology is limited

in terms of data availability and perhaps, some basic assumptions, individual physical and chemical components of the model are measurable, and can be refined and modified, as new information becomes available.

Even in its present form the physical/chemical simulation model provides a good theoretical basis for assessing qualitatively and quantitatively the effects that atmospherically derived loadings of free hydrogen ions can have on lake alkalinity and commercial fish species. While the original model was designed for application on a regional scale, the system easily lends itself to use both on a lake basis and a watershed scale.

In the following pages the most important assumptions and limitations of the model are discussed.

1. Data Requirements

The data needed to operate the acidification model are relatively simple to acquire and are generally available in the scientific literature, and in government and university file reports and data bases. Corroborative data for the physical and biological components can be collected to improve the precision of the estimates as required by the user.

2. Use of Alkalinity Rather than pH

The use of pH as a measure of lake status and sensitivity is commonly encountered (Harvey and Beamish, 1972). However, since pH is a log scale, it is relatively insensitive to small changes which might be occurring in a lake/watershed system; such changes would go undetected owing to the precision of the monitoring techniques available. In addition, pH is a less conservative measure than alkalinity and may undergo significant daily and seasonal fluctuations due to changes in the ratio of photosynthesis and respiration, and hence the concentration of dissolved CO_2 in the water. However, by using alkalinity, which is a linear scale and a relatively stable water chemistry parameter, significant changes in a lake/watershed buffering capacity are more likely to be detected.

3. Component Basis

The model has been developed on a component basis; as well, the system is notoverly sensitive to any one input variable. This means that reasonable estimates of losses in alkalinity, commercial fish yields and species can be made, even if one or more of the variables are somewhat in error. Being developed on a component basis means that any one component can be refined and the model improved accordingly. Refinements are certain to enhance the predictive capabilities of the model, improving its utility.

4. Model Validation

It will be argued that the methodology presented herein can never be tested. However, the alkalinity/acid inputs from each source can be calibrated independently by full measurements. As information pertaining to each component is generated, the model will become progressively more refined. This process will permit spatial validation; however, temporal validation would require an extended timeframe or would need to be based on data collected for a shorter time period from sensitive lakes receiving large acid loads for which changes in alkalinity are detectible.

5. Focus on Clinal Losses in Fisheries Production

To date, the focus of many field and laboratory investigations has related to confirming certain critical or threshold pH values for aquatic organisms (Harvey et al., 1981). Such approaches ignore long term impacts on fisheries which occur between natural conditions in a lake and threshold points. The model quantifies the production lost between natural pH and threshold levels, in addition to extinction losses.

6. Use of Conventional Fisheries Management Techniques

The MEI is applied extensively by fisheries managers throughout Ontario. In this regard, it is the basis in Ontario for setting commercial fishing quotas in most lakes allocated for this use, for

estimating sustainable yield supply levels for Ministry of Natural Resources regional and district planning programs, and for evaluating recreational development and subdivision proposals on both private and Crown lands. Accordingly, use of the MEI is not new to fisheries managers; it is a conventional and proven technique.

7. Hydrological Parameters

Five sources of hydrological input are considered in the model, V_L, V_R, V_{PL}, V_G, and V_{eL}. Four of these have been measured in a number of locations, and reasonable estimates on a regional basis are available. The volume of groundwater, V G, is not available for Ontario (R.C. Hore, personal communication); additionally, measurements of groundwater flow to lakes, either directly or as base flow via inflowing streams, are quite restricted. Groundwater may contribute up to about 44% of a lake's total annual alkalinity according to the formulation used in this model for a lake having $[A_L] = 5$, $A_W = 500$, $z = 14$, $BS = 0.4$, although in the majority of cases, the value is less than 10%. The possibility of developing a significantly improved generalized estimate of V_G in the short term is small, owing to the expected high degree of variability associated with this parameter.

8. Lake Alkalinities ($A_L{}^o$)

Measured values of [$A_L{}^o$] are used for base year lake alkalinities and subsequent changes in [$A_L{}^o$] values are calculated internally by the model. This calibration procedure is an important process and is reasonably straightforward. The major limitation is the availability of suitable water chemistry and watershed data.

9. Soil Parameters

[A_R], runoff alkalinity, is a function of the overburden characteristics of a lake's watershed; it is the major driving parameter in the physical/chemical component of the model. There are a number of assumptions associated with its calculation, which are discussed in some detail below.

a) Soil Depth (S)

The reactive layer of soil with surface runoff is represented by this term; however, the depth of the layer varies seasonally and spatially within a watershed. Ideally, the total reactive soil mantle volume (m^3) should be divided by the watershed area to derive its mean depth; however, this would be a monumental task, even for one small watershed. In reviewing the sensitivity of the model to soil depth (Hough, Stansbury + Michalski and J.E. Hanna, 1981), this factor was determined to be a major determinant and therefore limited refinement to the estimates may be warranted.

b) Cation Exchange Capacity (CEC) and Bulk Density (C)

As is the case for S, CEC and C should be integrated and averaged over the watershed. Estimates of CEC and C for various soil horizons are available from diverse sources (e.g., Hoffman et al., 1962; Brady, 1974; J.R. Kramer, personal communication), although integrated values for the "reactive" soil layer are scarce. The model is similar in sensitivity to S, CEC and C.

c) Base Saturation (BS)

An integrated approach, as discussed for S, CEC and C, would be needed to calculate average BS values for a watershed. Generally, information on BS is less frequent than for the preceding soil parameters and, of all the soil parameters, it has the greatest influence on the rate of acidification and estimated alkalinities. Additionally, replenishment of BS through physical weathering or atmospheric deposition of basic cations is not activated in the model, although provision is made to include values if warranted. J.R. Kramer (pers. comm.) suggested that the contribution of physical weathering is not significant throughout most of Ontario over the time frame of our analysis. P.J. Dillon (pers. comm.) felt that, although substantial quantities of basic cations may be deposited in Ontario, virtually all of the material originates from local sources, resulting only in the relocation of the ions as opposed to importation from external sources. Accordingly, both of these parameters were given a zero value.

d) Watershed Area (A_W)

For most lakes, information on watershed areas was obtained from Ministry of Natural Resources; otherwise, areas were measured using a computer digitizer facility. However, the number and size of upstream lakes, and hence the contribution of alkalinity from these systems, were not considered due to the complexity of integrating this type of data in our extrapolation procedure. Essentially, all water and land upstream of a given lake were treated uniformly as land. Depending on the BS of the soils in the watershed and the rate of acidification of upstream lakes, this assumption could lead either to an underestimate or to an overestimate of the acidification rate. Ideally, the methodology should be applied on an integrated watershed basis.

e) Reaction of Hydrogen Ions

The hydrogen cycle is perhaps the most complex and ubiquitous of all elements in natural systems, yet this subject has received relatively little attention (Ulrich, 1980). The calculations assume that all hydrogen ions equilibrate though the entire reactive soil layer prior to discharge. During periods of high runoff and/or frozen or catorated soil conditions, complete reaction between deposited acidic compounds and the reactive soil layer is not likely. Internal sources (i.e., oxidation of pyrites and gypsum, nitrogen fixation, etc.) and uptake by woody vegetation are not included in the simulation. The incorporation of hydrogen

in standing timber and its subsequenet harvest may be a major source of hydrogen removal.

f) Runoff pH (pH_R) - Alkalinity [A_R] Relationship

The pH_R is a function of BS which is derived from regression analysis of a number of observed values (Harvey et al., 1981). pH_R is converted to alkalinity based on equilibrium concentrations of CO_2 between the atmosphere and runoff. The partial pressure of CO_2 may vary in the soil layer depending on rate of respiration and diffusion, thereby influencing the value of [A_R]. This relationship is also temperature dependent, and a constant temperature of 25°C has been used.

g) Other Sources of [A_R]

The derivation of [A_R] is based solely on chemical reactions of hydrogen ions with aluminum silicate soils through chemical weathering, that is, cation exchange. The presence of carbonates either in the reactive soil layer or in the bedrock contacting the runoff will result in substantially different runoff values, both in terms of alkalinity concentrations and total buffering capacity. Additionally, sources of alkalinity such as organic acids have not been considered.

10. Groundwater Alkalinities [A_G]

[A_G] is assumed to be constant for all lakes and over time. In

actual fact, the concentration varies according to residence time, P_{CO2}, bedrock chemistry and temperature. The unavailability of representative data for inflows to lakes precluded estimates for each lake. Changes in $[A_G]$ over time were not considered significant owing to the relatively large buffering capacity of aquifers, a function of the contact area and elevated P_{CO2} values. The assumed value of $[A_G]$ is conservative compared to recorded measurements (Wang and Chin, 1978). Furthermore, acidification of groundwater regimes has been reported in Scandinavia (Hultberg and Wenblad, 1980), and the constant value of $[A_G]$ could lead to a slower predicted rate of acidification than might actually be the case.

11. Autochthonous Alkalinities $[A_A]$

Alkalinity from phytoplanktonic primary production is a well-known phenomenon to limnologists (Lewin, 1962). Brewer and Goldman (1976) suggested a relationship between primary production and alkalinity; however, the question is not addressed as to what proportion is permanent or net alkalinity. The uptake of nitrate nitrogen and the production of organic material consumes protons, thus increasing alkalinity. On the other hand, organic decomposition leads to the release of humic acids and H^+. The net alkalinity is a function of H^+ permanently bound in organic detritus and/or exported from the lake. Measures of $[A_A]$ are not available, except through interpolated values from calibrated

watersheds (Harvey et al., 1980), nor have representative values been collected for a wide range of lake trophic states. H^+ ions can likewise be generated by the deposition of organic matter (i.e., leaf fall) directly into the lake, which would further affect these values (i.e., allochthonous input).

Primary production from phytoplankton is limited to the euphotic zone; in the model, the entire lake volume has been used as the productive zone. This assumption could be refined by developing a relationship between Secchi disc depth and fish community, or some similar means to estimate the euphotic zone on an extensive basis (see Department of Fisheries and Oceans, 1982). Accordingly, the estimates of alkalinity produced from phytoplanktonic primary production might be high, as they do not strictly reflect net gain on an annual basis, and they are a function of each lake's entire volume, not just the euphotic zone. Also, the approach excludes alkalinity generated from macrophytic and perphytic biomass. As well, the "oligotrophication" process associated with the phenomenon of acidification has not been incorporated into the model as a modifier of primary production.

12. Other In-lake Alkalinity Sources

As indicated earlier, there are a number of sources of alkalinity in the model, two of which are associated with the lake itself, namely, residual lake alkalinity, and autochthonously generated

alkalinity. A third possible internal source of alkalinity relates to resolution from sediments (see letter, T.G. Brydges to E. Piche, in Department of Fisheries and Oceans, 1982, in Appendix A). Phosphorus release from sediments has received considerable attention over the years (Lee, 1979; Golterman, 1973; Burns and Ross, 1972; Schindler et al., 1973 & 1974) and for the most part, it appears that the potential supply for resolution consists of inputs from not more than the top 2-3 cm of sediments. However, in the case of alkalinity supplied from lake sediments, the situation is more complex. Resolution would lead either to an increase or to a decrease in alkalinity, depending on the chemical composition of the sediments and the amount of organic matter present. Investigations of the importance of this potential source are currently underway (see letter, T.G. Brydges to E. Piche, DFO 1982, Appendix A); if it is found to be significant, it can be readily incorporated into the model as a function of lake area, mean depth, and residual lake alkalinity, or whatever the appropriate relationship is.

13. Model Calibration

The predictive ability of the model with regard to rate of acidification is difficult to test. However, if Henriksen (1980) is correct in that lake acidification can be viewed as a large scale titration, an alkalinity budget approach should result in valid predictions. For those systems where acidification has been

observed (Harvey et al., 1981), the model could be applied to determine differences between observed and predicted rates. This type of calibration has not been undertaken; however, the results of static calibrations for several lakes are presented in Department of Fisheries and Oceans (1982).

14. Acid Pulses

The single flush concept of the model precludes predicting and assuming the impact of short term pH and alkalinity fluctuations, due to inputs from snowmelt and heavy rainfall or runoff, as observed in some lakes (Jefferies et al., 1978). Associated with this problem is the question of the representativeness of water chemistry with respect to the annual alkalinity flux in a lake, such as predicted in the model. Taking this one step further, the question arises whether aquatic communities respond to ambient, maximum, or minimum alkalinities, or to some combination of these values. The alkalinity and total dissolved solids data are generally available from sources such as the Ministry of Natural Resources OFIS information base and/or the Ministry of the Environment's various lake survey research and monitoring programs. Most sampling generally occurs in late spring or summer, when lake alkalinities tend to be highest owing to autochthonous alkalinity production. Accordingly, the model would tend to underestimte measured summer values. On this point, similar problems have arisen in phosphorus budget models, which are also based on a

complete mixing, single flush concept; nonetheless, such models have produced reasonably good predictions and are generally well-accepted by scientists and various government agencies. The best approximation by field measurements of alkalinities predicted in our model would be obtained in late winter, prior to snowmelt concentrations.

15. Morphoedaphic Index (MEI)

a) As indicated earlier, Ryder's MEI is the basic predictor of pre-threshold effects in the fisheries response model. This formulation has been reviewed by a number of fisheries biologists and applied with apparent success over a wide geographical range (R. A. Ryder, personal communication). On the other hand, Schneider (1975) found the MEI to be a poor predictor of fish yields. Alternative predictors, including that proposed by Schneider (1975), have been based on variables such as a panfish index and a vegetational ranking system; such types of data are not generally available for Ontario's inland lakes, and therefore Schneider's approach is of restricted value to this study. Additionally, the MEI is designed for application over a broad geographical area, and represents an average yield equation over a variety of lake types. In cases such as those discussed by Schneider (1975), lake types and geomorphological settings were fairly uniform, and good estimates could be derived. The applicability of such an index on a broader scale and on a more

varied lake data base has not been demonstrated. Use of the MEI for fish yield estimation in Africa and Asia (R.A. Ryder, personal communication), and on a world-wide scale has been achieved with reasonable sucess using a climatic variable in the MEI (Schlesinger and Regier, 1982).

An essential yet problematic issue is the concept of sustainable yield and annual productivity. Only by examining long term data for intensively managed or regulated lakes with moderate to intensive fishing pressure, can an approximation of sustainable yield be derived. Ryder has acknowledged the limitations of his approach and has suggested that the MEI be used only as a first estimator in the absence of other fisheries information. As indicated earlier, the Ryder approach to estimating long term annual sustainable yield is suggested to be accurate to within a factor of two (Ryder, 1979). Ryder has, furthermore, limited the lake types and climatic region within which the MEI is applicable. The correlation noted by Schneider (1975) between his climate index and fish yield (r is between .70 and .74) supports this qualification; however, an appropriate coefficient to modify the MEI for climatic variables has not yet been developed.

b) The MEI was developed through regression analysis techniques, using data on cross-sectional spatial variation in lake chemistry and morphometry. In the model, the MEI is used an an estimator of temporal changes in lake chemistry. The validity of this approach

depends on the underlying relationships which provide for the predictive accuracy of the MEI; however, the axiom that correlation does not necessitate a causal relationship is a valid concern. A complete theoretical explanation for the predictive accuracy of the MEI has not yet been developed. Mean depth, the morphometric component, has classically been recognized by limnologists as influencing lake productivity; this has also been supported for fish yields by various researchers (Schneider, 1975). The edaphic feature, total dissolved solids, or, more specific to this study, alkalinity, is likely not limiting, even in soft-water lakes, to primary production or to fish growth, except at extremely low concentrations (Schindler, 1971; Harvey et al. 1981; and R. A. Ryder, personal communication).

Phosphorus is commonly the nutrient in limiting primary production in Ontario's inland freshwater lakes (Schindler et al., 1971; Michalski and Conroy, 1973; Michalski et al., 1975; Dillon et al., 1978), and correlations between total dissolved solids, alkalinity, and phosphorus may partially explain the correlation between the MEI and fish yield. Also, energy suppy to a lake is a contributing factor to fish yield; however, if the MEI is used within a relatively uniform climatic region, this factor (energy) need not be accounted for. The resolution of this dilemma will require an extensive research effort over an extended
at present, however, the MEI appears to offer the only practical means to estimate clinal changes in fish productivity owing to

inputs of mineral acids.

c) As a lake acidifies, its total dissolved solids content may decline slightly due to loss of bicarbonate; however, some of this loss is compensated by an increase in sulphate ions (Harvey et al., 1980). A potential problem could arise where a partially acidified lake has a significant proportion of sulphate ions which is not accounted for in the transformation of total dissolved solids to alkalinity. Fortunately, most if not all of the lakes used to develop the MEI equation were characterized by high proportions of alkalinity in their total dissolved solids (see Figure 6.3). However, caution is warranted if the model is applied to a specific lake or watershed system in which sulphate ions contribute substantially to the system's total dissolved solids content. Perhaps a greater problem is the estimation of total dissolved solids from conductivity; in this regard, when lakes are acidified, the ratio between total dissolved solids and conductivity is not constant.

16. Threshold pH Values

The model simplifies each fish species' response to acidification. A precise lethal mechanism is not stated; however, once the threshold is reached, it is assumed that the entire standing stock of that species would be removed, (see Appendix C). In reality, the response likely more gradual and is spread over a number of years. In fact, several authors (Loucks, 1981; Henriksen 1980) have commented that

near the end of the acidification process, lakes enter a phase of instability, with substantial fluctuations in akalinity and pH. In addition, the lethal threshold is likely a function of a variety of factors, such as concentrations of toxic heavy metals, habitat quality, location of spawning areas, predation rate including angling, and lake hydrologic characteristics. These factors might act independently in a particular lake; more likely, their close interrelationships preclude a definitive statement of lethal threshold.

As a practical alternative, reported values from field observations have been used to derive threshold pH values for each commercial fish species. These values were selected to include the cumulative effects of the influencing parameters described above. For example, the studies of Beamish and Harvey in the 1960's and 1970's on lakes in the La Cloche Mountains of northwestern Ontario were our primary sources of information in setting pH values for fish species. In addition to depressed lake pH, elevated levels of aluminum, fishing pressure, and perhaps even acidic spring pulses undoubtedly had some impact on fish species. However, the authors' observations likely reflected the net or integrated responses of all parameters on the various fish species, rather than pH alone.

Implicit in the thresholds is a partial accounting for spring pulses; however, it is important to understand that both the physical/chemical and biological models do not take into account

depressions of lake pH owing to snowmelt and heavy runoff and rainfall conditions. An entirely different approach would be needed to address this problem. (See limitation 14., Acid Pulses).

17. Allocating Fish Productivity to Species

The total fish yield for each lake has been allocated among species, as is the practice with fisheries managers in Ontario (Hough, Stansbury + Associates Limited, 1979 and Hough, Stansbury + Michalski Limited, 1981). These derivations (see Appendix C) are derived from observed proportions of total harvest and the community structure of various fish assemblages (Adams and Olver, 1977). By increasing the harvest pressure on a particular species, an increase in yield for that species might be possible; however, this increase in yield may occur at the expense of another species in the community and/or the overall stability of the fishery and its yield (Mr. R. A. Ryder, personal communication). The values used are considered to be optimum for long term sustainable yields.

18. Redistribution of Fish Productivity

After a species is lost from a fish community due to the threshold pH effect, it is assumed that a portion of the yield lost would be redistributed among those species remaining. Some fisheries managers are of the view that the vacated habitat might not be filled, so that the fish productivity contributed by that species

would be lost. On the other hand, some managers have argued that the concept of vacated habitat is not particularly relevant to fisheries productivity; as long as the basic biological energy flow is maintained in a system, it will be rechannelled through the fishery via alternative species. In this regard, the loss of a species from a fish community results in a functional redistribution among remaining species, and the productivity or yield realized by that species is dependent on its ability to replace functionally that lost species. Observations from the Killarney lakes partially support this perspective (Ryan, 1976).

In this study, only a portion of the yield lost is distributed among the species remaining. The uptake by the remaining species was estimated according to functional similarities between species lost and those remaining. Generally, as the number of remaining species decreased, the uptake proportion decreased, reflecting a decline in functional diversity and adaptability. Accordingly, the approach represents a compromise between the vacant habitat and the energy flow theories. The precise values for redistributing the yields are based on judgement and there is no supporting documentation for the values chosen.

19. The Lake Data Base

For each of the 107 inland lakes which were commercially fished in 1979, the lake acidification and biological response calculations were

undertaken and fish production (kg/year) and fish community (in terms of number of lakes) losses were estimated. The input morphometric, hydrologic, biophysical and chemical data for each lake were secured from existing files, government and scientific reports and from discussions with Ministry of Natural Resources fisheries managers throughout the province. In many cases, lake and watershed areas were determined by Hough, Stansbury + Michalski using a computer digitizer facility. Where data were not available, published information from nearby lakes and watersheds was used. Information for each lake is provided in the input data base of the computational framework; the data for each lake can be easily recalled and reproduced.

6.5 THE ECONOMIC VALUE OF THE IMPACT OF ACID DEPOSITION ON ONTARIO'S COMMERCIAL FISHERIES

The model described in the previous sections predicts changes in the productivity of various commercial fish species on a lake by lake basis due to increase in acidity. It is this model that has been incorporated in the computational framework provided to the Ministry of the Environment.

Since lake acidification would occur, albeit at a slow rate, in the absence of anthropogenic sources of hydrogen ion, the proper basis for assessing the economic impact of acid deposition is a comparison of fish yields with and without anthropogenic loadings of hydrogen ion. In effect, this would require the model to be run

twice, with and without anthropogenic loadings, so that differences in fish yields could be estimated and valued in economic terms.

A simpler approach, and the one adopted in this study, is to consider the impacts on fish yields of the net addition to total hydrogen ion loadings due to anthropogenic sources. This will affect the time at which the various threshold effects are predicted to occur, but since natural loadings of hydrogen ion are generally such a small proportion of the total loadings, the error introduced by this approach is likely to be minimal.

Estimation of the economic value of reductions in the maximum sustained yield (MSY) of a commercial fishery is complicated by the fact that a reduction in MSY may not necessarily entail a reduction in catch. This will be the case when the current or projected harvest is considerably below the MSY or quota, if one exists. To take these considerations into account, three possibilities are allowed for in the economic component of the fisheries model:

i) For species subject to quotas and fished at or near the quota (defined as 75% or more of the quota), any reduction in MSY is counted as an economic loss. The value of the loss is estimated by multiplying the reduction in yield by the price of the fish.

ii) For species not subject to quotas but harvested at or near MSY (i.e., equal to or greater than 75% of MSY), any reduction in

MSY is counted as an economic loss and valued at 1980 prices.

iii) In all other cases reductions in MSY are not considered to be economically significant.

Implementation of this approach requires, in addition to all of the information necessary for the biological component of the model, harvest data for each commercially fished lake considered at all susceptible to the effects of acid deposition. Such data for the year 1979 were obtained from the Ministry of Natural Resources. No change in annual harvest was projected over the study period, an assumption which is consistent with the historical record for the aggregate of northern inland lakes since 1941 (Ontario Ministry of Natural Resources, 1980).

It should be noted that the use of market prices for valuing yield changes assumes that there will be no significant changes in the costs of harvesting fish. This is a reasonable assumption to the extent that the predicted changes in MSY will be insufficient to affect fishing effort. (An attempt to estimate a cost function for commercial fishing based on information obtained from commercial fishermen on the Lake of the Woods, met with the following result. Of the nine species of fish commercially harvested in the lake, only four showed up as statistically significant in determining fishing costs. In three of these cases, the estimated unit cost exceeded the selling price of the fish. Owing to the small sample on which the costs were estimated, it was decided not to incorporate these results in the present study).

Chapter 7

BUILDINGS AND MATERIALS

CHAPTER SUMMARY

There is little information available specifically on the effects of acid deposition on buildings and materials. It is necessary, therefore, to exptrapolate results obtained from studies of the effects of air pollution in general. Relationships so derived provide the basis for the model of the impacts of acid deposition (wet only) on buildings and materials developed in this study and included in the computational framework. The chapter also includes sections on methodologies for assessing the economic cost impacts on historical buildings and water supply systems. No models of these are presently included in the computational framework.

7.1 BACKGROUND ON THE NATURE AND SCOPE OF THE IMPACTS

Several recent reviews of the effects of air pollution on materials have been published (Riederer (1974); Sereda (1977), Yocom et al (1977), OECD (1979), Nriagu (1978), Acres Consulting Services (1980), and the United States - Canada Memorandum of Intent on Transboundary Air Pollution (1981)). Of these only the United States - Canada Memorandum of Intent (1981) addresses the effects of acid precipitation. It is apparent that air pollutants damage materials by five mechanisms: abrasion, deposition and subsequent removal of particles, direct and indirect chemical attack,

and electro-chemical corrosion. Other climatic factors such as moisture, temperature, sunlight and air movement also affect the rate of deterioration of materials.

Many structural metals can be adversely affected by acid deposition through increased dissolution of protective surface oxides, or by attack on the metal itself. The most important criteria affecting the rate of metal corrosion are pollutant concentration (particularly SO_2) and time-of-wetness of the surface (Sereda (1977) and Mansfeld et al (1977)).

The effects of sulphur oxides on building stone have been extensively studied (Nriagu (1978) and the United States - Canada Memorandum of Intent on Transboundary Air Pollution (1981)). In the presence of moisture, carbonates in the stone materials are rapidly attacked by SO_2.

$$CaCO_3 + SO_2 + 1/_2O_2 \rightarrow CaSO_4 + CO_2$$

$$CaCO_3.MgCO_3 + 2SO_2 + O_2 \rightarrow CaSO_4 + MgSO_4 + 2CO_2$$

The end-products of these reactions are the relatively more soluble compounds, calcium sulphate, magnesium sulphate, and calcium bicarbonate. However, although the chemical reactions are simple in principle, the mechanism of deterioration associated with them is linked in a complex way to the physical properties of the stone such as porosity, permeability, water retention ability and calcite-dolomite ratio (Sengupta (1972)). One major mechanism by which acidic precipitation

damages stone is by causing increased permeation of pollutant-laden moisture to the fabric of the stone (Weaver (1981)). Much of the damage to building stone is attributable to the formation of hard, impenetrable "skins" on the surface. These skins, aided by freeze-thaw action, cause blistering, exfoliation and loss of cohesion of the surface. The conversion of carbonates to sulphates and subsequent crystallization within the cleavage planes of the stone cause efflorescence or crystalline spalling which cause flaking of the stone and exposure of fresh surface to attack.

Portland cement, mortar and concrete are attacked by sulphate, the hydrated calcium aluminate and/or calcium hydroxide component of the hardened cement paste being converted into ettringite (calcium sulphoaluminate hydrate) and gypsum. The stresses associated with the increase in volume of crystallization may lead to breakdown of the paste and ultimately of the mortar or cement (Sereda (1977)). Most of this kind of deterioration is associated with sulphate originally present in the mortar or cement material which is leached to the surface (Sereda (1977)). However, atmospheric pollutants and acid precipitation are expected to contribute incrementally to this deterioration. Works of art and frescoes are also liable to sulphate damage by the same mechanism (Riederer (1974), Yocom et al (1977), Nriagu (1978), Fassina (1978), and Lal Gauri et al (1981)).

Generally, glass as a building material is not affected by sulphates or acids in precipitation (Yocom (1976)). However, one type of glass which

is severely affected by air pollution and acidic precipitation is stained or highly decorative glass which is the most valuable type of glass in use. Painted glass used in historical buildings is particularly affected by sulphur pollution, which attacks the paint causing loss of artistic expression of the glass painting. Damage also occurs to the glass itself. Potassium, one of the main components of this type of glass, is leached out of the silica matrix by acidic pollutants and precipitation causing the glass to become opaque. Simultaneously, at the surface, a layer is formed consisting of dust particles cemented together with sulphates (particularly gypsum) formed by the corrosion on glass by the action of acidic water. Below this layer, small craters appear in the glass around the impurities and from these networks of cracks spread out all through the glass causing massive deterioration (Riederer (1974)).

Protective coatings are also susceptible to deterioration from air pollutants and acid precipitation. Linseed-oil based paints and alkyd paints (two commonly used house paints) are severely degraded by sulphur pollutants (Weaver (1981)). SO_2 has been shown to increase the drying time of oil based paints and discolouration of certain pigmented paints have been observed (Yocom et al (1977)). No studies of the effects of sulphur oxides on water-based paints were found, but it has been speculated that SO_2 and other water-soluble acid gases could interfere with the stability of the polymer-pigment water emulsion and produce an incomplete paint film.

Little information relating material deterioration and atmospheric levels

of NO_x and nitrates is available. However, nitric acid has a very deleterious effect on most metals, more so than sulphuric acid or hydrochloric acid (McLeod (1969)).

Most studies document the effects of sulphur oxides on materials and show that without the presence of moisture, there would be little, if any, corrosion, even in the most severly polluted environment (Yocom (1977)). This indicates that acid precipitation may have an incremental effect on deterioration because the sulphur species in precipitation is already present as sulphate and can directly attack the material surface.

Scope of the Impacts: Problems of Assessment

Thus a wide range of building materials and structures can be affected, including structures of a historical interest and works of art. The discussion of the method for estimating the economic damages associated with these impacts considers general buildings and structures, which are discussed in section 7.2, separately from structures of a historical interest, which are examined in section 7.3.

Acid deposition can also have an impact on man-made structures through its impact on the chemical composition of the water supply. An increase in the corrosiveness of water can result in water supply system components' being attacked; this is of concern primarily because of the potential release of chemicals deleterious to human health.

An approach to estimating the economic damages associated with the impact of acid deposition on water supply systems is discussed in Section 7.4.

Before the specific methods are discussed, it is important to note that an assessment of the effects of atmospheric pollutants on man-made structures must take several complicating factors into consideration:

- Building materials experience degradation, even in the absence of deposition of atmospheric pollutants. Thus, it is important to differentiate between expected weathering and accelerated deterioration attributable to deposition.

- The effects of local pollution sources confound any assessment of damages related to acidic precipitation and pollutants transported from great distances. For instance, if local SO_2 emissions are deposited on local buildings and are subsequently oxidized to sulphate, it is impossible to distinguish this local source of sulphate from the secondary sulphate deposited by acidic precipitation which may have originated at a source several hundred kilometers away. Thus, any effects caused by acid deposition must be assessed as an additional contribution to deterioration processes which are already occurring due to local emissions.

- The effects of atmospheric pollution and acid deposition vary with the season of the year. Air pollution damage to materials

is maximized when significant moisture is present at the surfaces in combination with low temperatures (just above freezing); conditions typical of late winter - early spring. This season is also typified by increased heating requirements resulting in higher levels of airborne pollutants, by more frequent freeze-thaw episodes, and by accumulations of acidic pollutants in the snow layer. Thus, most damage may occur over a fairly short season during the year.

- Not all surfaces of structural materials are affected equally by deposition of atmospheric pollutants and acid deposition. During a precipitation event, precipitation falls on only part of a building or structure, its impact being dependent on such factors as wind conditions, precipitation quantity and structure orientation and configuration. Also, the precipitation run-off will wash previously deposited pollutants and their reaction products along the surface. This tends to concentrate pollutant attack along overhangs, cornices or on the lower extremities of structures.

7.2 AN APPROACH TO CALCULATING THE ECONOMIC IMPACT OF ACID PRECIPITATION ON BUILDINGS & STRUCTURES

7.2.1 Description of the Approach

The methodology for estimating economic damages was derived from Salmon (1970). While there are a number of weaknesses with this approach, data and project budgetary constraints ruled out the development of a comprehensive alternative methodology.

Using Salmon's approach, the material specific damage for a region in Ontario is given by:

$$D_r = C \times L \times V \times E \times I_r \times P_r$$

Where:

D_r = Annual damages in region r ($1980)
C = Consumption of material in Ontario in 1979 ($1980)
L = Estimated economic life of the material
V = Value added factor to reflect material's value in place
E = Exposure factor (%)
P_r = (Population in region r)/(Ontario population)
I_r = Interaction Value

All of the values used in the calculations are presented in Table 7-1.

It should be stressed that the methodology includes a procedure for estimating only a sample of the materials likely to be affected by acid precipitation. The selection of materials to include in the methodolody was guided by two considerations; information available on material

corrosion related to air pollution and the relative economic importance of such corrosion identified in the literature.

Future work should broaden the range of material examined.

VALUE OF MATERIALS CONSUMPTION (C)

Some materials consumption data have been included in the computational framework. They are based on the figures Acres (1980) derived from Statistics Canada data. These 1979 estimates were converted to 1980 dollars via the price index for non-residential building materials. The 1979 index is 208.6; the 1980 index 230.2 (Bank of Canada Review, September 1981.). See Table 7-1 for the estimates used.

ECONOMIC LIFE (L)

The economic lifetimes estimated by Salmon (1970) were adopted directly. See Table 7-1.

VALUE ADDED FACTOR (V)

Salmon (1970) derived what he termed a 'labor factor' to adjust for each material's value in place. Salmon's values were based upon 1968 U.S. economic conditions. His labour factors have been adjusted to reflect 1979 economic conditions in Ontario. In 1968 the ratio of total construction costs to materials costs in Ontario was 2.19 (derived from Statistics Canada 64-201); in 1979 the ratio was 2.58. Each of Salmon's material specific labor factors have been multiplied by (2.58/2.19). See

Table 7.1

Buildings and Materials: Summary Data

Material	Ontario Consumption ($ million)	Economic Life (Years)	Value Added Factor	Exposure Factor	Interaction Value
Concrete	342.9	40	3.1	.34	3.2×10^{-5}
Zinc	36.5	36	2.7	.47	1.71×10^{-4}
Aluminum	192.2	16	2.4	.34	1.42×10^{-6}
Copper	156.9	22	2.8	.34	1.58×10^{-5}
Paint	93.7	4	3.9	.47	6.72×10^{-5}
Nickel	30.6	14	2.7	.34	8.02×10^{-5}

Table 7-1 for the values used.

POPULATION (P_r)

County specific population estimates for 1980 were provided by the Ministry of Treasury and Economic Affairs. These estimates have been allocated to each of the study's 64 regions and recorded in the datafiles.

EXPOSURE FACTOR (E) AND INTERACTION VALUE (I_r)

Salmon's exposure factors were estimated for airborne pollutants. Salmon's factors have been reduced by 50% to adjust for exposure to wet deposition.

An interaction value (I_r) has been specified for each material as a function of SO_4 deposition. These values have been used to estimate the region-specific corrosion of each material. For some of the materials examined, more recent work than that utilized by Salmon, has been scrutinized and forms the basis of the estimated interaction values. Salmon's interaction values have been adopted in those instances where no more recent information is available.

The general approach used to adjust the exposure factor and the interaction values is discussed in the next section along with a detailed, material by material derivation of interaction values.

7.2.2 The Derivation of Exposure Factors and Interaction Values

As previous reviews have shown (see Shaffer(1981), for example) virtually no direct information is available on the physical impacts of acidic precipitation on man-made systems. Some work has been done on corrosion related to specific airborne pollutants, such as sulphur dioxide. However, very little is known about the impact of such pollutants as nitrates or nitrogen oxides, and no study results are available concerning the relative impacts of long range versus short range transport. The effects of such factors as acidity, the synergistic relationship between different types of pollutants, and the reactivity of pollutants deposited by wet versus dry means are all poorly understood.

The approach of the present study is to use existing information on corrosion associated with sulphur dioxide as a basis for estimating potential damages due to acid rain. This is done in two steps. First, the regional estimates of wet deposition of sulphates from anthropogenic sources have been converted to an "equivalent" concentration of sulphur dioxide. An "equivalent" concentration of SO_2 represents the concentration of SO_2 which would produce an annual deposition (as Sulphur) at a material surface equivalent to the deposition of sulphur (as Sulphate) by acidic precipitation.

Second, the corrosion rates for sulphur dioxide are then adjusted as follows to take into account the wet, rather than dry nature of the

deposition:

- Salmon's exposure factor for each material is reduced by 50% to reflect the fact that not all the surfaces subject to corrosion from airborne pollutants will be open to deposition by rain.
- The interaction value which is the estimated annual corrosion associated with the SO_2 equivalent is reduced to 40% of its original level. This is done to reflect the fact that sulphates in acid rain are likely to be in contact with materials a shorter time than airborne pollutants.

The effect is to reduce the corrosion rate for waterborne sulphates to 20% of the corrosion rates that are associated with SO_2. This figure probably errs on the 'conservative side', yielding an underestimate of damages.

It has been suggested that dry deposition from long range transport could be at least as great as wet deposition. The corrosion associated with dry deposition would be much greater on a unit by unit basis -- the effects would be 100% of the equivalent SO_2 measure (compared to the estimated 20% used in this study for wet deposition).

7.2.3 The Determination of Interaction Factors for Selected Materials

The interaction factor is defined as the average fractional loss of useful life per year for any material exposed in a polluted environment above the deterioration suffered in an unpolluted environment. Thus, the physical loss per year (L) due to a given pollutant is calculated by

$$L = \frac{M \times r \times F_i}{Q_{av.}} \qquad (7.2)$$

Where M is the quantity of material affected, r is the interaction rate, F_i is the pollutant concentration and $Q_{av.}$ is the appropriate physical unit in which material loss is estimated (e.g. thickness, weight, percent tensile strength). Such values are available for only a few materials and are mostly determined for sulphur dioxide interaction. A recent study (Mansfeld (1980)), part of the Regional Air Pollution Study (RAPS), examined the effects of pollutants, particularly sulphur pollutants, on various materials. Corrosion rates were measured over a 30 month period, and correlations were made with pollutant levels. However, no precipitation sampling or correlations were performed.

Precipitation in the form of rain affects corrosion by giving rise to an appreciable layer of moisture at the material surface and by adding corrosion stimulators in the form of H^+ and SO_4^{2-}, but also by washing off the pollutants, principally sulphates, deposited during the preceding dry period. Whereas the first two processes promote corrosion, the third may decrease corrosion.

Kucera (1976) describes a study where, on exposure of steel plates, the skyward side corrosion represented 55% of total corrosion in rural and marine environments compared to groundward side corrosion, and only 37% in urban-industrial environments. This was ascribed to the washing effect of rain being more pronounced in the more heavily polluted areas.

As the results of this study represent the only quantitative measurements of the effects of acidic precipitation found in the current literature, it was decided to use the figure of 40% of the corrosion effects of an "equivalent" concentration of SO_2 to assess the effects of acid precipitation. CANSAP data for 1979 are used to assess sulphur deposition by precipitation in Ontario. Assuming a deposition velocity of SO_2 of 0.9 cm/second(17), each 1.0g of S deposited per m^2 per year represents an average SO_2 concentration of 7.0 ug/m^3 or 2.7 ppb. Equivalent SO_2 concentrations for any amount of deposited sulphur are calculated by:

$$y = \frac{x}{0.14} \qquad (7.3)$$

where x = S deposition in g/m^2/yr

and y = SO_2 concentration in ug/m3

The above reasoning is applied, along with published effects of SO_2 on materials, to arrive at estimates of damage caused by acid precipitation to particular materials. These estimates are, of necessity, very crude as they are based on very limited data and do not account for such effects as differing meteorology, variations in precipitation quantity and composition, and different interaction effects for different materials.

Because of the uncertainty concerning the value of the interaction factors, a probablistic range has been specified in the computer model for all of the material interaction factors. The range for each has been set at a factor of 2 in either direction: one-half the estimated value interaction factor as the lower limit and twice the value as the upper limit. The probability distribution has been specified so that there is an equal probability of the value falling anywhere within the range (the form termed "unirand" in IFPS).

ZINC

Zinc is widely used in galvanizing to protect ferrous metals, particularly steel, from atmospheric corrosion. The corrosion of zinc is accelerated in an atmosphere containing moisture, SO_2 and other acidic pollutants through a process in which the basic carbonate coating that forms naturally in the air, and normally protects the metal, is destroyed. Guttman (1968) measured the sensitivity of zinc to environmental factors and found the time of wetness and atmospheric SO_2 content during the time that the exposed panels were wet exert critical effects on the corrosion rate of zinc. He developed an empirical equation relating these factors and corrosion:

$$Y = 0.00546A^{0.8152}(B + 0.02889) \qquad (7.4)$$

where Y = corrosion loss (mg per 3" x 5" panel)

A = time of wetness (hours)

B = atmospheric SO_2 content during time panels are wet (ppm)

A study by Haynie and Upham (1970) found that zinc corrosion varied linearly with sulphur dioxide concentration and relative humidity according to the equation.

$$Y = 0.001028(H - 48.8)S \qquad (7.5)$$

where Y = Zinc corrosion rate (um/yr)

H = average relative humidity (%)

S = average SO_2 concentration (ug/m^3)

um/yr = micrometres per year

ug/m^3 = micrograms per cubic metre

Using an ambient SO_2 concentration of 0.015 ppm (40 ug/m^3) typical of Ontario urban areas (Air Quality Monitoring Reports, Ontario MOE (1978)), figures of 3000 hours average time-of-wetness per year and 80% relative humidity reported for Ottawa (Sereda (1977)), and the transformation from weight loss to thickness loss in coated 4" x 6" panels for zinc (Mansfeld (1980)),

$$d = \frac{4.52\ m}{t} \qquad (7.6)$$

where m = weight loss (g per 4" x 6" panel)

t = time in years

d = change in coating thickness (um/year)

The above equations yield zinc corrosion rates of 1.23 um/year and 1.28 um/year respectively, a very good agreement. Mansfeld (1980) measured differential corrosion rates in the St. Louis area for galvanized steel panels to be between 0.79 and 0.64 um/year with SO_2 levels ranging from undetectable to 26 ppb over a 24 month period and relative humidity levels in the 60-80% range. Thus, the available information agrees with the interaction expressed by the above equations.

Using Haynie and Upham (1970) the corrosion rate is given by: $3.20736 \times 10^{-2} \times SO_2$. The thickness of zinc in place is given by Salmon (1970) as 75 um. Adjusting for this and the 40% equivalent corrosion rate assumed for acid precipitation yields an interaction factor of $1.71 \times 10^{-4} \times SO_2$.

COPPER

Kucera (1976) reports corrosion rates for copper of 1.0 um/year in an urban environment (approximately 70 ug/m^3 SO_2) an 0.6 um/year in a rural environment (approximately 10 ug/m^3 SO_2). Linear extrapolation of these figures indicates that copper corrodes at a rate of approximately 0.5 um/year in the absence of SO_2 pollution. Thus the effect of pollutants must be estimated as an incremental corrosion rate. Using these figures for copper, the corrosion rate is $1.26 \times 10^{-2} \times SO_2$. Using the thickness of 320 um given by Salmon (1970) and adjusting for the 40% factor yields

an interaction value of 1.58 x 10^{-5}.

PAINT

Extensive testing of the weatherability of paints has been carried out for many years, but there have been few attempts to identify the effects of individual pollutants. In a laboratory study, Spence and coworkers (1975) investigated the effect of sulphur dioxide, nitrogen dioxide, ozone and relative humidity on the erosion of oil-base house paint, acrylic latex house paint, vinyl oil paint and acrylic oil paint. The tests on acrylic latex house paint had to be discontinued because of corrosive attack of the aluminum substrate, presumably by the paint's acting as a semipermeable membrane allowing SO_2 through to attack the aluminum, but excluding oxygen which would tend to passivate the aluminum. Of the other three types of paint tested, the largest erosion rate was found for oil-based house paint with considerably lower rates for vinyl and acrylic oil paints. However, although regression equations were devised equating SO_2 and relative humidity levels with erosion rate, the fact that this was a laboratory study of gaseous interactions makes it difficult to apply the results to acidic precipitation effects. Kucera (1976) quotes a lifetime for an 80 um coating of alkyd paints of corresponding type of about 10 years in a rural atmosphere, and about 8 years in an urban atmosphere. Using Kucera's figures for sulphur levels, this means that about 2 um/year of paint thickness is lost due to about 60 ug/m^3 of SO_2. In the RAPS study (1980), weight loss tests were carried out on oil-base (63.5 um thickness) and latex (38 um thickness)

house paints. These studies showed integral corrosion rates over a 30 month period of 25.1 $ug/cm^2.mth$ to 44.0 $ug/cm^2.mth$ for latex paint and 17.8 $ug/cm^2.mth$ to 24.4 $ug/cm^2.mth$ for oil-based paint for SO_2 concentrations ranging from undetectable to 23 ppb.

For the purposes of this study, the Kucera figures for alkyd paints are used as a guideline for all paints which are likely to be eroded by acid precipitation. Linear interpolation leads to a corrosion rate of $6.72 \times 10^{-3} \times SO_2$. With a thickness of 40 um, and adjusting for the 40% factor, this yields an interaction factor of $6.72 \times 10^{-5} \times SO_2$.

CONCRETE

No studies were found which related corrosion rates of concrete with ambient levels of sulphur pollutants. However, the mechanism by which sulphate solutions attack Portland cement are well documented (Nriagu (1978)). The deterioration can be attributed to three basic reactions:

(a) the dissolution (or removal) of $Ca(OH)_2$, a major binding agent in cement;

(b) the hydrolysis of the various cement components, leading ultimately to the formation of a residue consisting of silica gel, aluminum hydroxide gel, and ferrioxide gel;

(c) the conversion of the cement components to the more soluble gypsum.

In addition, formation of insoluble calcium sulphoaluminate, notably ettringite ($3\ CaO \cdot Al_2O_3 \cdot 3CaSo_4 \cdot 31H_2O$), within the pore structure of the concrete causes surface spalling due to crystal volume changes below the

concrete surface.

In the absence of further information, the interaction value estimated by Salmon(1970) has been adopted. Adjusting Salmon's interaction value for the 40% factor gives: $3.2 \times 10^{-5} \times SO2$.

ALUMINUM

No relevant corrosion studies for aluminum were identified. Adjusting Salmon's estimates gives an interaction value of: $1.42 \times 10^{-6} \times SO_2$.

NICKEL

No recent work on pollutant-related corrosion of nickel was identified. Adjusting Salmon's estimates yields an interaction value of: $8.08 \times 10^{-5} \times SO_2$.

MARBLE

Although extensive studies have been carried out on the mechanism of sulphur pollutant attack on marble and stone surfaces, particularly applied to studies of deterioration of historical structures, there have been few studies which measured actual corrosion rates of marble. The RAPS study (1980) included marble (White Cherokee Marble) as one material studied. Differential corrosion rates of approximately 130 um/year were measured over a 30 month period, with an average ambient SO_2

concentration of 75 ug/m3. As the thickness of marble depends heavily on its use and no comparable value of thickness is available from Salmon, an interaction value was not calculated.

7.2.4 Limitations of the Approach

The weakness of including estimates for only a sample of materials likely to be affected by air pollution has already been noted.

The approach used by Salmon (1970) while providing a consistent basis for the evaluation of the economic impacts associated with air pollution, demonstrates a number of weaknesses, which are useful to identify for purposes of qualifying the estimates made using the approach and identifying research and study priorities:

1. Salmon (1970) uses current sales (actually production) of each material as a proxy for the material "used up" by the economy in each year. This "used up" amount is comprised of a portion of the materials purchased in that year and of materials purchased in previous years, which constitute a portion of the capital stock. Thus it is only under special circumstances (eg. a steady state economy) that the proxy will accurately capture the desired consumption quantity. The use of this proxy can create special problems for discounting methods, such as the present value approach adopted for the present study.

2. Salmon uses the economic life of each material to indicate expected lifetime - the reduction in lifetimes asociated with increased corrosion is taken to be a reduction in economic lifetime. While it is clear that increased corrosion will decrease a material's physical

lifetime, it is less clear that this reduction will be felt fully as a reduction in the economic lifetime of the material.

3. The exposure factors, thickness of materials in use, etc. adopted by Salmon (1970) were established as the basis of aggregate and sometimes relatively crude information. This is understandable, given the scope of Salmon's study and the information available to him. Because of the importance of this factor for the damage estimates, it would be useful to attempt to establish, perhaps through "sample" investigation of the built environment, some empirically derived exposure factor estimates. For starters, the results of studies such as that by Stankunas et al. (1981) could be scrutinized for any implications concerning the values adopted by Salmon.

4. Salmon's (1970) labour, or value added factor accounts for the cost of putting the material in place. It does not consider the value of the service rendered by the material. As Salmon (1970) expresses it:

> "Several important factors are not included in the estimate of value of materials exposed to pollution damage because the data are not available. The economic production data in the study reflect the final product value rather than material value. The economic data do not reflect a value of service provided by the product." p.9.

The failure of a small nickel plated computer component, due to the corrosive effects of air pollution (eg. the dry deposition of sulphur from long range transport) could have economic costs many orders of

magnitude greater than its market price. This possibility results in an underestimate of the damages attributable to acid deposition.

5. The interaction values adopted by Salmon (1970) were based on the scientific data accumulated to that point on the corrosive effects of air pollution. Damage estimates are only as good as the scientific evidence that supports them.

Mention has been made throughout this chapter on the dearth of scientific information. Relatively solid evidence has been accumulated concerning the impact of a few specific air pollutants on a few materials under particular given conditions (eg. the impact of SO_2 or zinc, given temperature and level of wetness). Virtually nothing has been done which can be directly and unproblematically applied to the calculation of the impact of acid precipitation on buildings and structures.

7.3 HISTORICAL BUILDINGS AND STRUCTURES

It may be argued that the negative effects of acid deposition on structures of historical interest results in irreversible, non-restorable loss, and that such loss, if it can be valued in economic terms at all, must be valued in the way that the loss of any unique item is. Such an argument, while it may have merit, places the estimation of the impacts of acid rain on historic structures outside the realm of market prices, and thus beyond the terms of reference of this study.

An alternative approach is to accept the possibility of restoring buildings through repair, as imperfect as this may be in retaining their true historic value. The economic impact of damages may then be approximated as the cost of repairing the deterioration caused by acid precipitation.

To utilize this method, it is necessary to identify both the physical damages associated with acid deposition and the costs of repairing the damage. This would constitute a 'case study' of the costs of acid rain for a particular subset of buildings and structures.

Concerning the cost of repair, the Ontario Heritage Foundation has maintained cost data on a number of restoration projects across the province. This should serve as a useful data source for any case study of the impacts of acid deposition on historical buildings.

The task of identifying the physical damages to historical structures associated with acid rain is more difficult. Inventories of buildings and structures of historical interest do exist, as does a voluminous literature concerning the effects of air pollutants on historical structures and artifacts. However, the vast majority of this literature documents the mechanisms by which various pollutants (principally SO_2) attack the materials of construction or describes methods of conserving such structures. No literature was found in which direct measurements of the rate of deterioration of the materials was carried out in conjunction with monitoring of air pollutants. Recourse to studies of modern materials which are similar in composition to historical materials and for which some interaction data are available, is therefore necessary.

Building stone is of two kinds, calcareous, such as limestone and marble, and siliceous, such as sandstone or granite. The mechanism of deterioration associated with air pollutant or acidic deposition attack on these types of building stones is linked in a complex way to the physical properties of the stone such as porosity, permeability and water retention ability. For example, an Ontario sandstone, Nepean sandstone, is fairly impermeable to water, whereas other sandstones commonly used in Ontario, but imported from Ohio or New Jersey, can be quite permeable (Weaver (1981)). Siliceous building stones are expected to show similar chemical deterioration to that demonstrated by concrete. Deterioration of limestone and marble are expected to proceed in a similar way to that described above for marble. The deterioration of native rock carvings will depend on the type of rock.

While this provides a starting point for the estimate of damages due to acid deposition, some of the problems identified in Section 7.2.3 remain. Ignoring the difficulty with the lack of scientific information on corrosion rates, which can only be obtained through well designed research, the issue of 'value of putting in place' versus 'value in service' may remain unsettled.

7.4 WATER SUPPLY SYSTEMS

Water with a low pH can attack water supply systems, damaging the systems and releasing chemicals which are deleterious to human health -- for example, asbestos from cement-asbestos pipe and heavy metals which are a particularly important problem where such piping is still in use, (See Ryder (1980)). Acid rain could contribute to the increased corrosion of such systems by decreasing the pH of the water supply.

7.4.1 An Approach for Estimating the Economic Impact of Acid Precipitation on Water Supply Systems

Water can be classified according to its "aggressiveness", that is, its tendency to attack materials, such as piping, in water supply systems. For example, an "aggressiveness" index is used to classify drinking water supplies in Ontario. The ASTM aggressiveness index is defined as:

$$ASTM = ph + \log (ah) \qquad (7.6)$$

Where: pH = water pH
a = alkalinity
h = calcium hardness.

Waters are classified as aggressive if the index reading is under 10, moderately aggressive if the reading is 10 - 12 and non-aggressive if the reading is greater than 12.

Aggressive waters can be rendered non-aggressive through the addition of such chemicals as soda ash and lime. Some municipalities in Ontario (eg., Sudbury) have already installed treatment systems to deal with waters which read too high on the ASTM scale.

Using the ASTM index as a guide to the point at which water supply systems require counteracting measures to prevent the release of undesirable substances, the economic impact of acid precipitation can be estimated in the following manner.

MUNICIPAL WATER SYSTEMS

1. Calculate the current ASTM aggressiveness index for the municipal water supply systems in Ontario (this has already been done for approximately 500 communities by the Ministry of the Environment).

2. Identify those systems which already have treatment systems to counteract the already aggressive water supply systems. For these municipalities:

   2.1 Calculate the likely impacts of acid deposition on the pH of the water supplies over the study period.

   2.2 Using the ASTM index calculate the increase in aggressiveness associated with acid precipitation.

2.3 Calculate the operating costs of increasing the chemical input to counteract this increased aggressiveness. The operating cost for a given municipality in year 1 would, therefore be given as:

$$A_1 = P_{1c} \times Q_{1c} + P_{1L} \times Q_{1L} + P_{1O} \times Q_{1O} \qquad (7.7)$$

Where:

A_1 = Total Operating Cost

P_{1c} = Price of Chemicals used

Q_{1c} = Quantity of Chemicals used

P_{1L} = Price of Labour (Wage Rate)

Q_{1L} = Quantity of Labour used

P_{1O} = Price of Other Items used

Q_{1O} = Quantity of Other Items used

The quantities of chemicals, labour and other items are only those employed as a result of the decrease in pH associated with acid deposition. The quantity of chemicals used would be directly proportional to the pH reduction and annual gallonage handled by the system; the increase in other inputs will be less. (It should be noted that the increased costs are likely to be very slight, given the low incremental costs of increased chemical input).

The present value of these costs would be calculated as:

(2) $$\sum_{t=1}^{n} \frac{At}{(1+d)^t}$$

Where:

A_t = Cost in year t

d = discount rate

n = time horizon (years)

3. For the municipalities in Ontario (the vast majority) which do not already have water treatment systems to counteract water aggressiveness, the following steps should be taken:

   3.1 Calculate the likely impacts of acid deposition on water pH over the study period.

   3.2 Using the ASTM index to calculate the increased aggressiveness associated with the acid deposition, identify those municipalities for which the water becomes aggressive as a result of acid deposition.

   3.3 Estimate the cost of purchasing, installing and operating systems for the municipalities identified in 3.2.

The present value of the cost for a given municipality of this occurring would be therefore:

$$\frac{K}{(1 + d)^j} + \sum_{t = j}^{n} \frac{B_t}{(1 + d)^t} \qquad (7.9)$$

Where:

K = Capital Cost of the Water Treatment System

j = Year in Which the System is Installed

B_t = Operating Cost of the System in $Year_t$.

The annual operating cost (B_t) differs from the cost calculated in equation (7.7) in that the total cost of operating the system is included.

PRIVATE WATER SUPPLY SYSTEMS

A number of private water supply systems, such as those installed and operated by cottagers could also be affected by acid precipitation. The approach to calculating these costs would be the same as for the public systems; the costs of the systems, however, would differ.

DATA REQUIREMENTS AND AVAILABILITY

The Pollution Control Branch of the Ministry of Environment has calculated the aggressiveness index (ASTM) calculations for a large number of municipalities, based on water sampling already undertaken.

Municipal water treatment systems are commercially available; their capital and operating costs are well defined; information on these costs derived from feasibility studies and operating experience is readily available. (See, for example, Gore & Storrie (undated) and from the Ministry of the Environment.) Information on the nature of the individual municipal systems, which is required to calculate the likely operating costs of the systems (eg., gallonages) is also easily obtained.

One potential problem relates to those municipalities which derive their drinking water from ground water sources. The potential relationship between acidic precipitation and ground water pH is not well understood.

While treatment systems for the private water supplies are available they tend to be costly. It is possible that a simpler and cheaper approach could be developed, especially if the market for such systems increased (for example, due to increased concern about water softness).

APPENDIX A

ACID DEPOSITION SCENARIOS FOR ONTARIO

This appendix sets out the base year data on acid deposition in Ontario and explains the assumptions used to derive future deposition scenarios. These scenarios are common to the analysis of the impacts of acid deposition on all of the receptor categories considered in this study.

A.1 TOTAL LOADINGS OF MINERAL ACIDS

Table A.1 shows the major ion loadings in 1979 for each of the 64 regions. These loadings were obtained by visual interpolation of the CANSAP data plotted on figures A1 to A4. The computational framework allows consideration of the implications of various user-specified patterns of changes over time in these deposition rates:

1. constant
2. increasing at an annual percentage rate
3. decreasing at an annual percentage rate.

The user is not at liberty to vary the deposition rates of the four ions independently of one another (though this could be allowed for by only minor programming changes). It was thought better to build in a scenario-generating mechanism that recognized the interrelationships among the deposition rates of the four ions. For example, sulphates and hydrogen ions are likely to be positively correlated since they are both derived

TABLE A1

ACID DEPOSITION DATA FOR ONTARIO (1979)

MAJOR ION LOADINGS BY REGION
($meq/m^2/year$)

SITE REGION	DISTRICT	H^+	NH_4^+	$SO_4^=$	NO_3^-
1E Hudson Bay	1	5	5	15	4
	2	5	7	20	4
	3	5	7	22	7
	4	5	5	20	10
2E James Bay	1	10	15	33	15
	2	10	15	37	19
	3	15	15	45	20
3E Lake Abitibi	1	20	25	48	20
	2	35	32	75	25
	3	35	30	60	25
	4	45	35	120	40
	5	50	35	100	35
	6	50	30	70	30
4E Lake Temagami	1	55	35	130	42
	2	65	40	135	45
	3	65	40	115	48
	4	65	35	85	45
	5	55	30	75	40
2W Big Trout Lake	1	5	10	25	7
	2	5	10	22	7
	3	10	15	35	13
3S Lake St. Joseph	1	8	18	35	14
4S Lake Wabigoon	1	10	13	20	15
	2	10	15	25	15
	3	10	24	35	15
	4	10	20	35	15
	5	10	24	35	15
5S Lake of the Woods	1	10	14	20	15
	2	10	14	22	18
3W Lake Nipigon	1	15	25	55	17
	2	20	25	70	17
	3	25	25	85	20
	4	20	28	75	20
	5	25	30	100	30

SITE REGION	DISTRICT	H^+	NH_4^+	$SO_4^=$	NO_3^-
4W Pigeon River	1	25	25	50	25
	2	25	25	70	30
5E Georgian Bay	1	70	45	135	50
	2	75	50	135	55
	3	85	45	130	55
	4	80	42	125	55
	5	90	35	105	60
	6	75	30	100	50
	7	85	42	125	60
	8	95	40	115	65
	9	105	30	110	65
	10	100	32	105	63
	11	90	35	115	68
	12	85	35	115	68
6E Lake Simcoe-Rideau	1	60	55	130	63
	2	55	55	135	62
	3	55	60	135	62
	4	55	60	135	64
	5	50	65	138	63
	6	70	50	125	65
	7	65	45	120	63
	8	70	40	120	70
	9	75	38	120	72
	10	65	41	120	74
	11	65	40	120	70
	12	65	37	120	65
7E Lake Ontario	1	45	35	145	55
	2	50	45	130	60
	3	65	45	125	63
	4	65	45	125	65

from the oxidation of sulphur oxide gases into sulphuric acid. Consequently, using the deposition data on which Table A1 is based, a regression equation was estimated to predict hydrogen ion deposition as a function of sulphate deposition (all units are $meq/m^2/year$):

$$H^+ = \underset{(.0868)}{.50342} SO_4 + 1.2992 \qquad a.1$$

$$r^2 = .66$$

(The standard error of the coefficient is shown in parentheses).

The inclusion of nitrates in equation a.1 does not improve the prediction of hydrogen ion deposition owing to the high degree of collinearity between sulphates and nitrates. Accordingly, therefore, a second equation was estimated to predict nitrate deposition from sulphate deposition:

$$NO^-_3 = \underset{(.045)}{.45272} SO_4 + .11698 \qquad a.2$$

$$r^2 = .84$$

Nitrogen deposition as ammonia was taken into account by regressing ammonia on sulphates (equation a.3):

$$NH^+_4 = \underset{(.046)}{.283} SO_4 + 4.702 \qquad a.3$$

$$r^2 = .66$$

Rather than deal with two equations for nitrogen (a.2 and a.3), a single equation (a.4) was derived by recognizing that ammonia contains 3.44 times as much nitrogen per unit as a unit of nitrate:

$$NO^{-}_{3} = 1.4278SO_{4} + 16.3128 \quad \text{a.4}$$

Equations a.1 and a.4 are used in the computational framework so that, for any projection of sulphate deposition, total hydrogen ion and nitrate (including ammonia as nitrate) deposition is estimated in a way that is consistent with the available data

A.2 ACID DEPOSITION FROM ANTHROPOGENIC SOURCES

The overall purpose of the study is to help assess the extent of damages (or benefits) from emission sources over which man has control. Therefore, it is important to distinguish between anthropogenic and non-anthropogenic deposition of mineral acids. Unfortunately, apart from the work by Galloway and Whelpdale (1980) on sulphate deposition in North America, there are little scientific data on which such a distinction for the other acid forming gases can be based. Nevertheless, the distinction is so important from the point of view of policy analysis that some approach to this question is better than assuming that all loadings came from anthropogenic sources.

Acid deposition from anthropogenic sources were estimated with equations a.5 - a.7 (where the prefix °n° signifies loads from natural sources and all units are meq/m^2/year).

Anthropogenic hydrogen ion:

$$_nH^+ = 0.2519 \times \text{Precipitation rate (cm/yr)} \qquad a.5$$

Equation a.5 converts precipitation with a pH of 5.6 to total hydrogen ion loadings (meq/m^2) from natural sources ($_nH$).

Anthropogenic sulphate:

$$_nSO_4^{=} = (_nH^+ - 1.2992)/0.50342 \qquad a.6$$

Equation a.6 is a rearrangement of equation a.1 and derives the sulphate loadings from anthropogenic sources from the estimated hydrogen ion loadings obtained from a.5.

Anthropogenic nitrate:

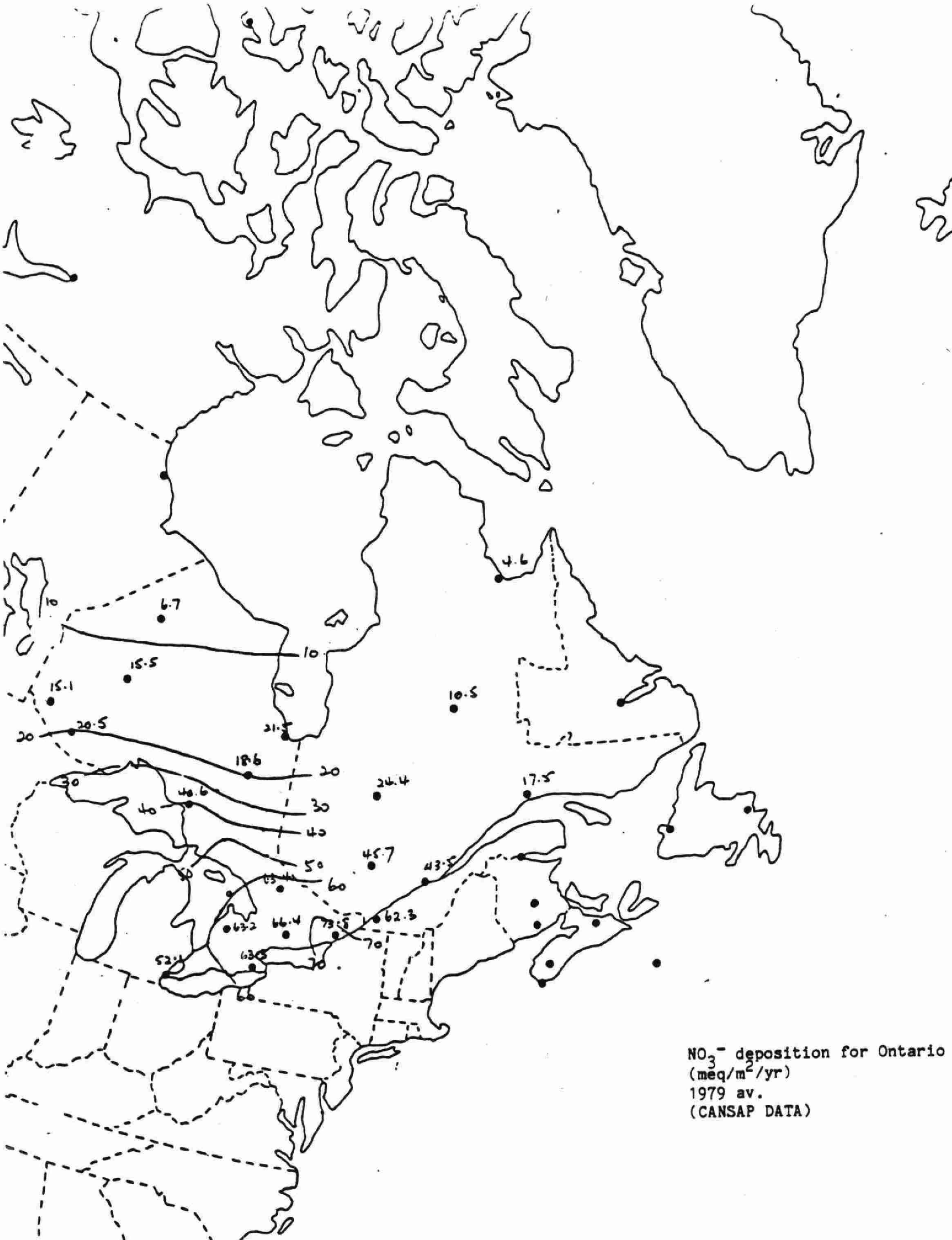
$$_nNO^-_3 = (1.4278\,_nSO_4^{=}) + 16.3128 \qquad a.7$$

Equation a.7 is obtained by substituting the estimated natural sulphate loadings into equation a.4.

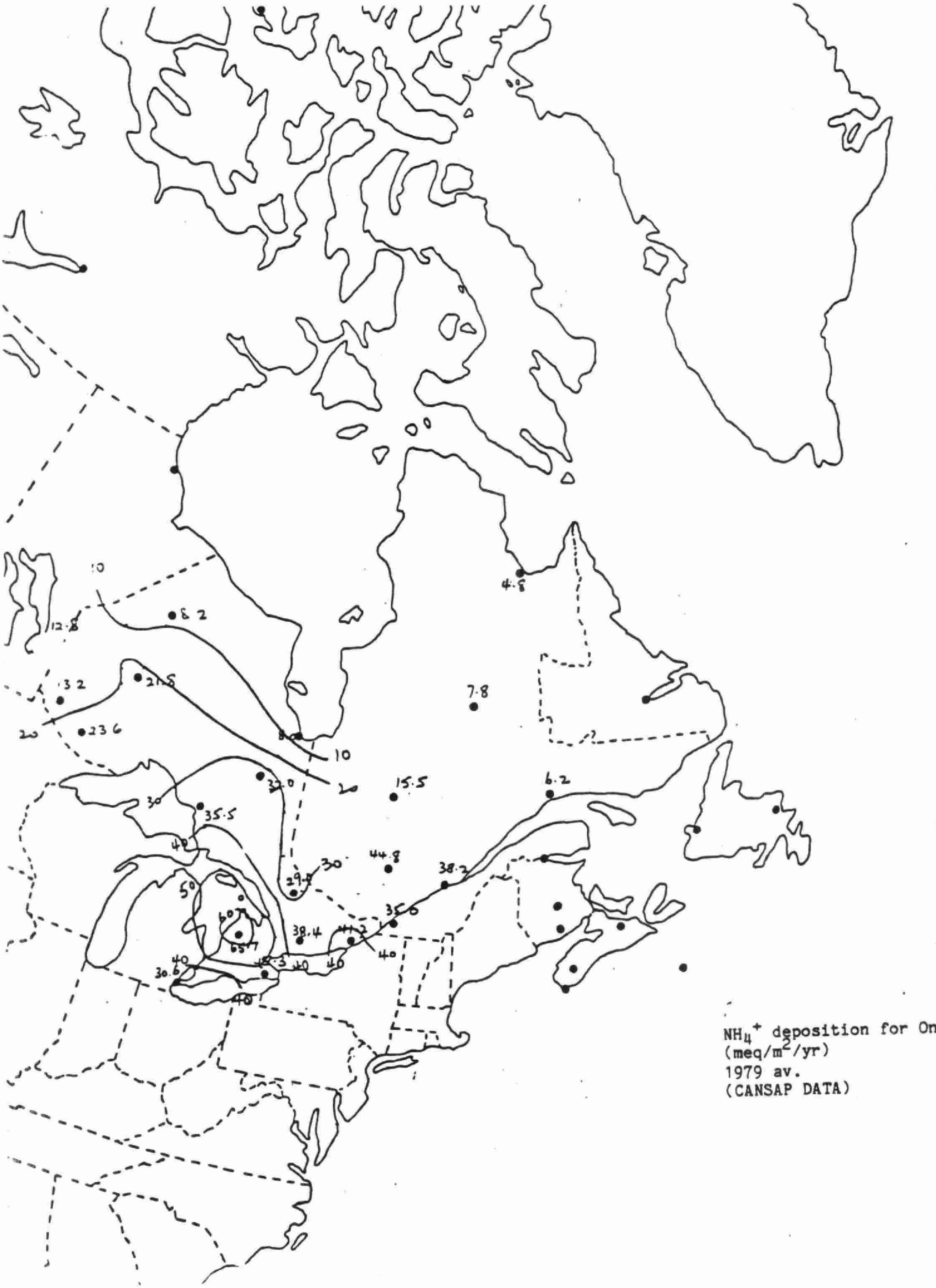
Wet and Dry Deposition

It should be noted that the CANSAP data only measure wet deposition of mineral acids. No equivalent data obtained from a sampling network

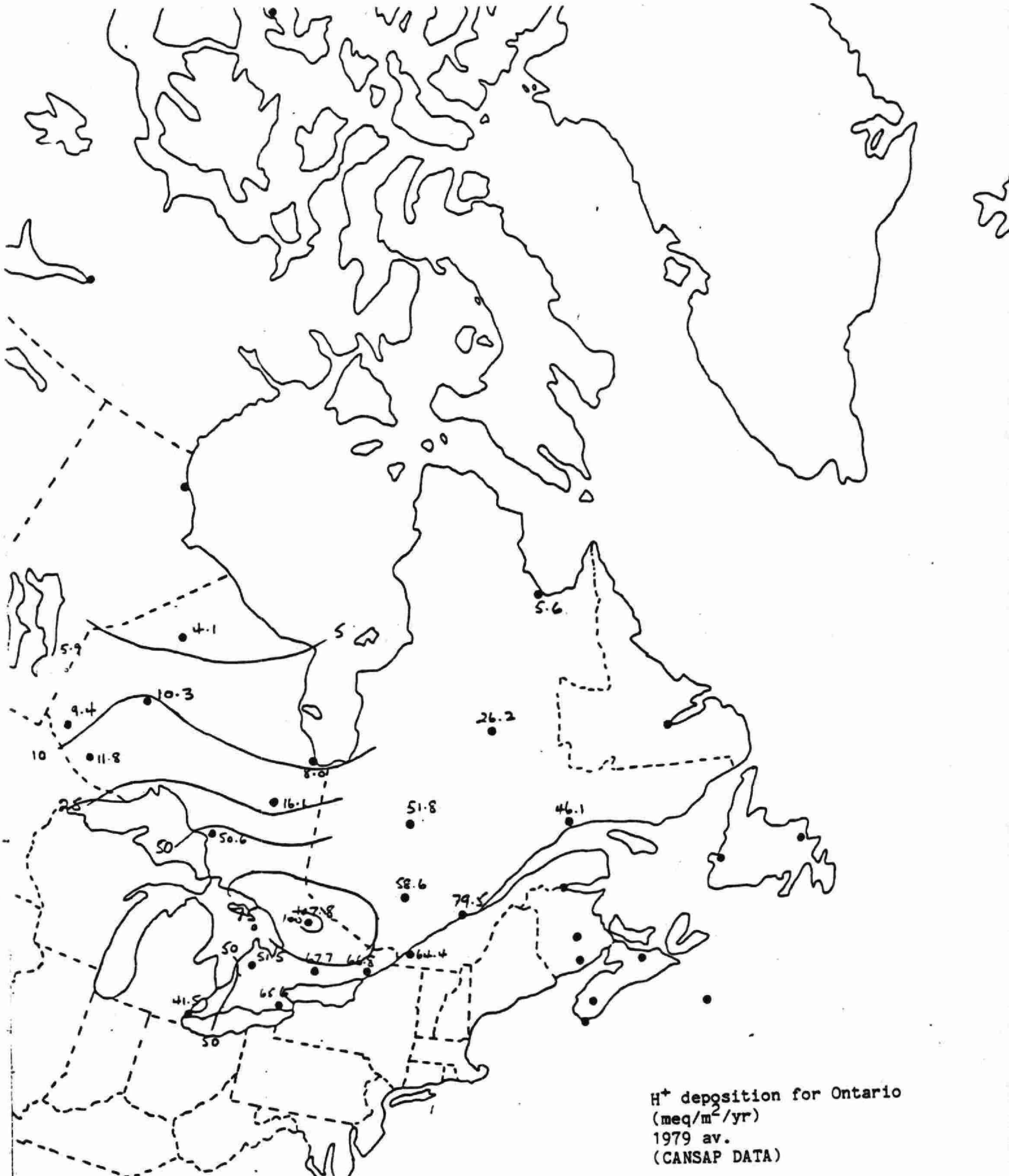
Incorporation of dry deposition into the deposition scenarios could be based on an assumed relationship between wet and dry deposition with corresponding changes in some of the dose-response functions to reflect differential impacts.



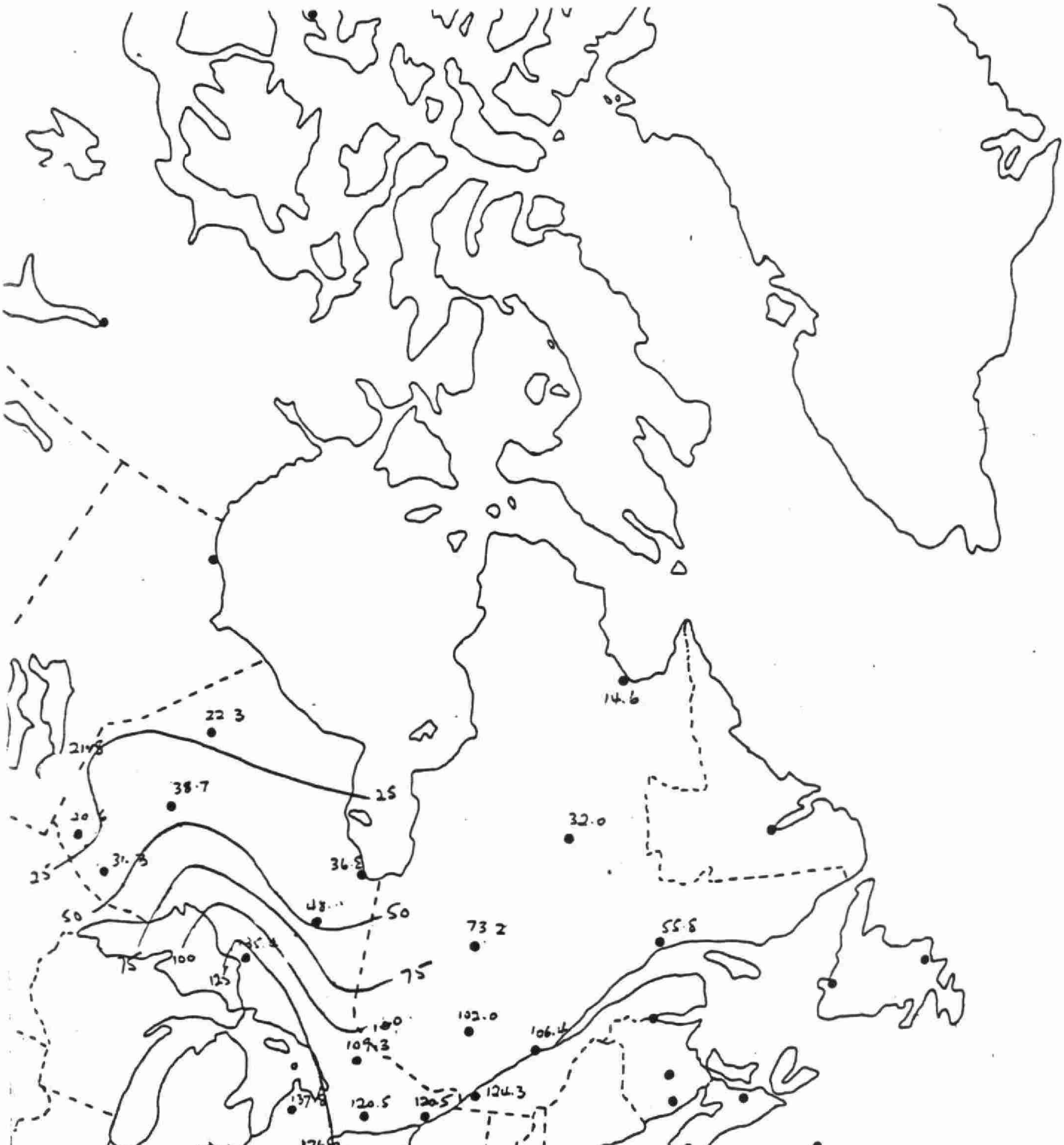
NO_3^- deposition for Ontario
($meq/m^2/yr$)
1979 av.
(CANSAP DATA)



NH_4^+ deposition for Ont[illegible]ri
($meq/m^2/yr$)
1979 av.
(CANSAP DATA)



H^{+} deposition for Ontario
(meq/m^{2}/yr)
1979 av.
(CANSAP DATA)



$SO_4^{=}$ deposition in Ontario
($meq/m^2/yr$)
1979 av.
(CANSAP DATA)

APPENDIX B

COMMERCIAL FISH COMMUNITY CATEGORIES AND THE PROPORTION OF SUSTAINABLE YIELD WHICH CAN BE ATTRIBUTED TO INDIVIDUAL SPECIES

Fish Community Number	Species Commercially Harvested	% of Total Amount Sustainable Yield Allocated to Species	Alkalinity (mg/l)	Lake Name	Lake Number	MNR DISTRIC
1.	lake whitefish	40%	31	MacDowell	14	Red Lake
	yellow pickerel	25%	20	Upper Goose	106	"
	northern pike	15%	14	Kirkness	102	"
	coarse fish	20%	20	Barton	95	"
			25	Little Trout	76	"
			28	Favourable	9	"
			40	McCoy	18	"
			22	Silcox	105	"
			40	Dinorwic	83	Dryden
			50	Wunnummin	22	Sioux Look
			29	Cat	31	"
			70	Shibogama	27	"
			41	North Caribou	17	"
			69	Wintering	40	Ignace
			50	Makokibatan	38	Geraldton
			65	Winisk	26	"
			55	Nibinamik	23	"
			20	Alphretta	4	Gogama
2.	lake whitefish	30%	33	Pakwash	79	Red Lake
	burbot	15%	30	Lac Seul	75	"
	sucker	15%	27	Wabigoon	82	Dryden
	yellow pickerel	25%	30	Lake St. Joseph	30	Sioux Look
	northern pike	15%	40	Round	16	"
			15	Sowden	68	Ignace
			29	Basket	67	"
			59	Kenogamisis	41	Geraldton
3.	lake whitefish	40%	23	Old Shoes	101	Red Lake
	yellow pickerel	25%	20	Pikangikum	103	"
	northern pike	15%	77	Stull	6	"
	sucker	20%	19	Stout	97	"
			24	East	8	"
			20	Sharpstone	98	"
			22	Cobham	10	"
			30	Maynard	88	Kenora
			30	Oak	89	"
			13	Dryberry	62	"
			30	Cedar	93	Dryden
			30	Wabaskang	91	"
			32	Windigo	12	Sioux Loo
			32	Upper Windigo	13	"
			50	Batchelor	21	"
			29	Kapikik	30	"
			35	Opakopa	15	"

Fish Community Number	Species Commercially Harvested	% of Total Amount Sustainable Yield Allocated to Species	Alkalinity (mg/l)	Lake Name	Lake Number	MNR DISTRICT
			50	Ponask	7	Sioux Lookout
			77	Little Blackbear	19	"
			47	Wigewascence	28	"
			48	Pinemuta	24	"
			30	Zionz	33	"
			30	Kinloch	20	"
			21	Jackfish	50	Fort Frances
			20	Lac des Mille Lacs	55	Thunder Bay
			25	Mojikit	35	Nipigon
			48	Whitewater	36	"
			45	Black Sturgeon	2	"
			59	Meta	42	Geraldton
			58	Ara	43	"
			69	Wintering	40	"
			60	Wapikopa	25	"
			20	Mattagami	45	Gogama
			14	Minisinakwa	46	"
4.	lake trout	25%	15	McCusker	99	Red Lake
	northern pike	10%	20	Deer	11	"
	yellow pickerel	15%	30	Long	39	Geraldton
	lake whitefish	30%				
	coarse fish	20%				
5.	lake trout	25%	24	Confusion	90	Red Lake
	lake whitefish	30%	26	Birch	32	"
	northern pike	10%	19	Atikwa	60	Kenora
	yellow pickerel	15%	24	Rowan	61	"
	sucker	20%	31	Bad Vermillion	53	Fort Frances
			26	Mount	52	"
			22	Sturgeon	74	Ignace
			28	Lake of Bays	73	"
			15	Caribou	37	Nipigon
6.	lake whitefish	30%	28	Trout	77	Red Lake
	yellow pickerel	10%	28	Woman	80	"
	northern pike	10%	16	Musclow	94	"
	burbot	25%	27	Berens	104	"
	lake trout	25%	24	Red	78	"
			13	Roderick	100	"
			15	Moar	96	"
			13	Dogtooth	63	Kenora
			28	North Eagle	86	"
			27	Sand	66	"
			41	Wine	92	Dryden
			15	Eagle	85	"

APPENDIX B

Fish Community Number	Species Commercially Harvested	% of Total Amount Sustainable Yield Allocated to Species	Alkalinity (mg/l)	Lake Name	Lake Number	MNR DISTRIC
			42	Gullwing	87	Dryden
			21	McCrea	34	Sioux Looko
			19	Indian	70	Ignace
			17	Barrel	71	"
			27	Paguchi	72	"
			50	Onaman	3	Nipigon
			28	Nipissing	5	North Bay
7.	northern pike	20%				
	yellow pickerel	20%				
	lake whitefish	30%				
	white bass	5%				
	sturgeon	5%				
8.	lake whitefish	35%	41	Marshall	44	Geraldton
	yellow pickerel	25%				
	northern pike	15%				
	burbot	10%				
	sucker	10%				
	yellow perch	5%				
9.	lake trout	30%	33	Arrow	1	Thunder Bay
	lake whitefish	40%				
	coarse fish	30%				
10.	lake trout	20%	45	Nipigon	45	Nipigon
	lake whitefish	25%				
	northern pike	10%				
	yellow pickerel	16%				
	sucker/chub	10%				
	burbot	10%				
	yellow perch	4%				
11.	lake trout	25%	20	Confederation	81	Red Lake
	lake whitefish	35%	47	Crow	57	Kenora
	northern pike	15%	36	Upper Manitou	49	Dryden
	sucker	25%	36	Lower Manitou	51	Fort Frances

Fish Community Number	Species Commercially Harvested	% of Total Amount Sustainable Yield Allocated to Species	Alkalinity (mg/l)	Lake Name	Lake Number	MNR DISTRIC
13.	lake trout	10%	25	Dogpaw	58	Kenora
	lake whitefish	25%	25	Caviar	59	"
	northern pike	10%				
	crappie and rock bass	5%				
	sucker	25%				
	yellow pickerel	25%				
14.	sturgeon	5%	23	Rainy	48	Fort Fr ce
	lake whitefish	25%	24	Namakan	54	"
	chub/sucker	10%				
	northern pike	15%				
	burbot	15%				
	rock bass/crappie	5%				
	sauger/yellow pickerel	25%				
15.	sturgeon	5%	26	Lake of the Woods	56	Fort Franc and Ke or
	lake trout	5%				
	lake whitefish/herring	20%				
	northern pike	15%				
	sucker	10%				
	bullhead	5%				
	burbot					
	rock bass/crappie	5%				
	yellow perch	5%				
	sauger/yellow pickerel	20%				
16.	lake whiterish	40%	20	Aragon	47	Gogama
	northern pike	30%				
	sucker	25%				
17.	lake whitefish	75%				
	coarse fish	25%				

APPENDIX C

pH Thresholds and Species Composition

Fish Community Number	Proportion of MEI Above pH 5.7	First pH Threshold Species Lost and MEI Uptake	Second pH Threshold Species Lost and MEI Uptake	Third pH Threshold Species Lost and MEI Uptake	Fourth pH Threshold Species Lost and MEI Uptake
1. lake whitefish	40%	-	-	-	
yellow pickerel	25%	-	-	-	
northern pike	15%	20%	-	-	
coarse fish	20%	30%	35%	-	
2. lake whitefish	30%	-	-	-	-
burbot	15%	25%	35%	40%	-
sucker	15%	25%	-	-	-
yellow pickerel	25%	-	-	-	-
northern pike	15%	20%	25%	-	-
3. lake whitefish	40%	-	-	-	
yellow pickerel	25%	-	-	-	
northern pike	15%	20%	-	-	
sucker	20%	30%	35%	-	
4. lake trout	25%	-	-	-	-
northern pike	10%	10%	15%	-	-
yellow pickerel	15%	15%	-	-	-
lake whitefish	30%	35%	-	-	-
coarse fish	20%	25%	35%	40%	-
5. lake trout	25%	-	0	-	-
lake whitefish	30%	35%	0	-	-
northern pike	10%	15%	25%	-	-
yellow pickerel	15%	20%	0	-	-
sucker	20%	25%	35%	40%	-
6. lake whitefish	30%	35%	-	-	-
yellow pickerel	10%	20%	-	-	-
northern pike	10%	15%	25%	30%	-
burbot	25%	25%	35%	40%	45%
lake trout	25%	-	-	-	-

Fish Community Number	Proportion of MEI Above pH 5.7	First pH Threshold Species Lost and MEI Uptake	Second pH Threshold Species Lost and MEI Uptake	Third pH Threshold Species Lost and MEI Uptake	Fourth pH Threshold Species Lost and MEI Uptake
7. northern pike	20%	20%	30%	35%	-
yellow pickerel	20%	20%	-	-	-
lake whitefish	30%	30%	-	-	-
white bass	5%	-	-	-	-
sturgeon	5%	5%	10%	-	-
8. lake whitefish	35%	-	-	-	-
yellow pickerel	25%	-	-	-	-
northern pike	15%	20%	20%	-	-
burbot	10%	15%	25%	30%	-
sucker	10%	15%	-	-	-
yellow perch	5%	10%	-	-	-
9. lake trout	30%	-	-	-	
lake whitefish	40%	45%	-	-	
coarse fish	30%	35%	40%	-	
10. lake trout	20%	-	-	-	-
lake whitefish	25%	30%	-	-	-
northern pike	10%	10%	15%	20%	-
yellow pickerel	16%	16%	-	-	-
sucker/chub	10%	10%	20%	-	-
burbot	10%	10%	15%	20%	25%
yellow perch	4%	4%	5%	-	-
				-	-
11. lake trout	25%	-	-	-	
lake whitefish	35%	40%	-	-	
northern pike	15%	20%	35%	-	
sucker	25%	35%	-	-	

Fish Community Number	Proportion of MEI Above pH 5.7	1st pH Threshold Species Lost and MEI Uptake	2nd pH Threshold Species Lost and MEI Uptake	3rd pH Threshold Species Lost and MEI Uptake	4th pH Threshold Species Lost and MEI Uptake	5th pH Threshold Species Lost and MEI Uptake
13. lake trout	10%	-	-	-	-	-
lake whitefish	25%	30%	-	-	-	-
northern pike	10%	10%	25%	45%	-	-
crappie and rock bass	5%	-	-	-	-	-
sucker	25%	25%	40%	-	-	-
yellow pickerel	25%	30%	-	-	-	-
14. sturgeon	5%	5%	5%	-	-	-
lake whitefish	25%	28%	-	-	-	-
chub/sucker	10%	10%	15%	-	-	-
northern pike	15%	15%	20%	25%	-	-
burbot	15%	15%	20%	25%	30%	-
rock bass/crappie	5%	-	-	-	-	-
sauger/yellow pickerel	25%	25%	-	-	-	-
15. sturgeon	5%	5%	5%	-	-	-
lake trout	5%	-	-	-	-	-
lake whitefish/herring	20%	25%	-	-	-	-
northern pike	15%	15%	20%	30%	-	-
sucker	10%	10%	15%	-	-	-
bullhead	5%	5%	5%	10%	20%	30%
burbot	10%	10%	10%	15%	20%	-
rock bass/crappie	5%	-	-	-	-	-
yellow perch	5%	5%	-	-	-	-
sauger/yellow pickerel	20%	20%	-	-	-	-
16. lake whitefish	40%	-	-	-	-	-
northern pike	30%	35%	40%	-	-	-
sucker	25%	30%	-	-	-	-
17. lake whitefish	75%	-	-	-	-	-
coarse fish	25%	40%	-	-	-	-

BIBLIOGRAPHY

Abrahamsen, G., (1980), "Acid Precipitation, Plant Nutrients and Forest Growth", Ecological Impact on Acid Precipitation, Drablos, D. and Tollan, A. (eds.), pp.58-63

Abrahamsen, G. et al, (1980), "Effects of Artificial Acid Rain and Liming on Soil Organisms and the Decomposition of Organic Matter", Effects of Acid Precipitation on Terrestrial Ecosystems, Hutchinson, T. C. and Havas, M. (eds.), pp.341-362.

Acres Consulting Services Limited,(1980), Effects of Air Pollution on Building Materials, Report to Ontario Hydro.

Adams, G.F. and Olver, C.H., (1977), "Yield Properties and Structure of Boreal Period Communities in Ontario", J. Fish,. Res. Board Can., 34: 1613-1625.

Air Quality Monitoring Reports, Vol. I., Ontario Ministry of the Environment, 1978.

Almer, B., Dickson, W., Ekstrom, C. and Hornstrom, E., (1978), "Sulphur Pollution and the Aquatic Ecosystem", In: Sulfur in the Environment, Part II, Ecological Impacts, Nriagu, J.O., (ed.), J. Wiley and Sons Inc., New York, N.Y. pp.271-311.

Almer, B., (1972a), "Effects of Acidification on Fish Populations in Lakes on the Swedish West Coast", Inst. Freshwater Res., Drottningholm Inform. 12: 1-47.

Almer, B., (1972b), "Forsurningens Inverkan pa Fiskebestand i Vastkustsjoar", Information from Sotuattens-Laboratouet, Drottningholm, Nr.12. 47 pp.

Altshuller, A.P. and McBean G.A., (1979), The LRTAP Problem in North America: A Preliminary Overview, U.S.-Canada Research Consultation Group on LRTAP.

Anon, (1981), A Canadian Research Activity Catalogue on The Long Range Transport of Air Pollutants and Acidic Precipitation, Environment Canada, Toronto.

Anon, (April - June 1981), "Effects of Simulated Acid Precipitation on Composition of Percolate from Reconstructed Profiles of Two Northern Ontario Forest Soils", Canadian Forestry Service Research News, (April - June 1981).

Aber, J.D. et al, (April 1981), "Potential Effects of Acid Precipitation on Soil Nitrogen and Productivity of Forest Ecosystems", Proceedings on the Effects of Acid Precipitation on Ecological Systems: Great Lakes Region, Michigan State University.

Barrie, L.A., (March 1981), "Environment Canada's Long Range Transport of Atmospheric Pollutants Program: Atmospheric Studies", Paper presented at the Conference on the Effects of Acid Precipitation on Ecological Systems in the Region of the Great Lakes, Michigan State University.

Barrett, L.B. and Waddell T.E., (1973), Cost of Air Pollution Damage: A Status Report, NTIS Publication No. PB-222-040.

Beamish, R.J., Blouw, C.M. and McFarlane, G.A., (1976), A Fish and Chemical Study of 109 Lakes in the Experimental Lakes Area (ELA), Northwestern Ontario with Appended Reports of Lake Whitefish Ageing Errors and the Northwestern Ontario Baitfish Industry, Environment Canada, Fish. Mar. Serv. Tech. Rep. No. 607.

Beamish, R.J., (1976), "Acidification of Lakes in Canada by Acid Precipitation and the Resulting Effects on Fishes", Water Air Soil Pollut., 6: 501-514.

Beamish, R.J., (1975), "Long-Term Acidification of a Lake and Resulting Effects on Fishes", Ambio 4: 98-104.

Beamish, R.J., (1974), "The Loss of Fish Populations from Unexploited Remote Lakes in Ontario, Canada, as a Consequence of Atmospheric Fallout of Acid", Water Res., 8: 85-95.

Beamish, R.J. and Harvey, H.H., (1972), "Acidification of the La Cloche Mountain Lakes, Ontario, and Resulting Fish Mortalities", J. Fish Res. Board Can., 29: 1131-1143.

Bengston, C., C.A. Bostrom, P. Grennfelt, L. Skarby and E. Troeng, 1980. Deposition of nitrogen oxides to Scots pine (Pinus sylvestris L.) in Drablos, D. and A. Tollan (eds.), Ecological Impact of Acid Precipitation. Procds. Intl. Conf., Norway, 1980. pp. 154-155.

Bolin, B. et al, (1971), "Air Pollution Across National Boundaries - The Impact on the Environment of Sulfur in Air and Precipitation", Sweden's Case Study for the United Nations Conference on the Human Environment, Royal Ministry for Foreign Affairs and Royal Ministry of Agriculture, Stockholm.

Botkin, D.B., Janak, J.F. and Wallis, J.R., (1972), "Some Ecological Consequences of A Computer Model of Forest Growth", J. Ecology 60: 849-872.

Boyd W.H. and Fink F.W., (1974), Corrosion of Metals in the Atmosphere.

Brady, N.C., (1974), The Nature and Properties of Soils, McMillan Publishing Co., New York.

Braekke, F.H., (1976), Impact of Acid Precipitation on Forest and Fresh-water Ecosystems in Norway, Research Report No. 6, Summary Report on SNSF project, Aas, Norway.

Brewer, P.G. and Goldman, J.C., (1976), "Alkalinity Changes Generated by Phytoplankton Growth", Limnology and Oceanography, Vol.2: 1, pp.108-117.

Brisley, H.R., Davis, C.R. and Booth, J.A., (1959), "Sulphur Dioxide Fumigation of Cotton With Special Reference to its Effect on Yield", Agronomy Journal, Vol.51: 77-80.

Budd, W.W., Johnson, A.H., Huss, J.B. and Turner, R.S., (1980), "Aluminum in Precipitation, Streams and Shallow Groundwater in the New Jersey Pine Barrens", submitted to Water Resources Research.

Burno, N.M. and C. Ross, (1972), Project Hypo. An intensive study of the Lake Erie Central Basin hypolemnion and related surface water phenomenon. Canada Centre for Inland Waters, paper No. 6. United States Environmental Protection Agency, Technical Report TS-05-71-208-24. 182 pp.

Campbell G.G., Schurr G.G. and Slawikowski D.E., (1972), A Study to Evaluate Techniques of Assessing Air Pollution Damage to Paints, NTIS Publication No. PB-222-377.

Canada - United States Memorandum of Intent on Transboundary Air Pollution, 1981. Impact Assessment Work Group Interim Report.

Cogbill, C.V., (1977), The effect of acid precipitation on tree growth in eastern North America, Water, Air, and Soil Pollution. 8:89-93.

Cogbill, C., (1976), "The Effect of Acid Precipitation on Tree Growth in Eastern North America", USDA For. Serv. Gen. Tech. Rep., NE-23: 1027-1032.

Cogbill, C.V., (1975) Acid precipitation and Forest Growth in the Eastern United States, M.Sc. Thesis, Cornell University.

Cowling, E.B., (April 1981), "A Status Report on Acid Precipitation and its Ecological Consequences", Proceedings on the Effects of Acid Precipitation on Ecological Systems: Great Lakes Region, Michigan State University.

Cowling, E.B. (1980), Acid precipitation and its effects on terrestrial and aquatic systems, in Aerosols Anthropogenic and Natural Sources and Transport. Annals New York Acad. of Sci. 338:540-555.

Dahl, E., (1975), "Stability of Tundra Ecosystems in Fennoscandia", Ecological Studies. Analysis and Synthesis, Vol. 17, Fennoscandian Tundra Ecosystems, Part 2, Wielgolaski, F.E. (ed.), Springer-Verlag Berlin Heidelberg, New York.

Dahl, E. and Kielland-Lund, J. (1967), "On the Vegetation Types of Norwegian Conifer Forests in Relation to the Chemical Properties of the Humus Layer", Norwegian Forest Research Institute, Vollebekk, Norway.

Dahl, E. Selmer-Anderssen, C. and Saether, R., (December 1961), "Soil Factors and the Growth of Scotch Pine: A Statistical Re-Interpretation of Data Presented by Viro (1955)", Soil Science 92. No.6 367-371.

Department of Fisheries and Oceans, (1982), An Approach to Assessing the Effects of Acid Rain on Ontario's Inland Sports Fisheries, Prepared by Hough, Stansbury + Michalski Limited and J. E. Hanna Associates Inc., Draft Report.

Dillon, P.J. and F.H. Rigler, 1975. A simple method for predicting the capacity of a lake for development based on lake trophic state, J. Fish. Res. Board Can. 32:1519-1531.

Dillon, P.J., et al., (1978), "Acidic Precipitation in South Central Ontario: Recent Observations", Journal of Fisheries Research Board of Canada, 35, 809-815.

Dillon P.J. et al., (1979), "Acidic Lakes in Ontario, Canada: Characterization, Extent and Responses to Base and Natural Additions", Archives of Hydrobiology, 13:317-336.

Duvigneaud, P. and S. Denaeyer de Smet, (1970), Biological cycling of mineralism in temperate deciduous forests, in Analysis of Temperate Forest Ecosystems, ed. D.E. Reichle, pp. 199-225. Springer-Verlag, New York.

Evans, L.S., Conway, C.A. and Lewin, K.F., (Oct. 1980), "Yield Responses of Field-Grown Soybeans Exposed to Simulated Acid Rain", Ecological Impact of Acid Precipitation, Drablos, D. and Tollan, A. (eds.), pp.162-163.

Evans, L.S., 1980. "Foliar responses that may determine plant injury by simulated acid rain", in Polluted Rain.

Evans, L.S. and Curry, T.M. (1979), "Differential Responses of Plant Foliage to Simulated Acid Rain", Am. J. Botany, 66: 953-962.

Evans, L.S., Gmur, N.S. and DaCosta, F., (1978), "Foliar Responses of Six Clones of Hybrid Poplar to Simulate Acid Rain", Environmental and Experimental Botany, 17:145-149.

Evans, L.S., Gmur, N.S. and Dacosta, F., (1977), Leaf surface and histological perturbations of leaves of Phaseolus vulgaris and Helianthus annuus after exposure to simulated acid rain, Amer. Journal of Botany. 64: 903-913.

Evans, L.S., Gmur, N.S. and Kelsch, J.J., (1977), "Perturbations of Upper Leaf Surface Structures by Simulated Acid Rain", Environmental and Experimental Botany, 17:145-149.

Fassina, V., "A Survey of Air Pollution and Deterioration of Stonework in Venice", Atmos. Environ., 12, 2205 (1978).

Federal Treasury Board (1976), Benefit Cost Analysis Guide, Ottawa.

Fee, E.J., (1980), "Important Factors for Estimating Annual Phytoplankton Production in the Experimental Lakes Area", Can. J. Fish. Aquat. Sci., 37: 513-522.

Golterman, H.L., (1973), "Vertical movement of phosphate in freshwater", in Environmental Phosphorus Handbook, Edited by Griffith, E.J., Beeton, A., Spence, J.M., and Mitchell D.T. John Wiley and Sons, Inc., pp. 509-538.

Gore & Storrie Ltd., (undated), Report on the Proposal Treatment for the Loch Lomond Supply, prepared for the City of Thunder Bay.

Guttman, H., "Effects of Atmospheric Factors in the Corrosion of Rolled Zinc", in Metal Corrosion in The Atmosphere, ASTM STP No. 435, 1968, pp. 223-239.

Hales, J. M., (1981), "Precipitation Chemistry: Its Behaviour and its Calculation", in Air Pollutants and Their Effects on the Terrestrial Ecosystem, Krupa, S.V. and Legge, A.H. (eds.), John Wiley & Sons.

Harker, A.B., Mansfeld, F.B., Strauss, D.B. and Landis, D.D., "Mechanism of SO_2 and H_2SO_4 Aerosol Zinc Corrosion". Rockwell International Report to EPA, EPA-600/3-80-018 (NTIS PB80-167018), January 1980.

Harvey, H.H., Pierce, R.C., Dillon, P.J., Kramer, J.R., and Whelpdale, D.M., (1981), Acidification in the Canadian Aquatic Envionment. Scientific Criteria for Assessing the Effects of Acid Deposition on Aquatic Ecosystems, National Research Council Canada Report Number 18475.

Harvey, H.H., (Oct. 1980), "Widespread and Diverse Changes in the Biota of North American Lakes and Rivers Coincident with Acidification", in Ecological Impact of Acid Precipitation, Drablos, D. and Tollan, A. (eds.), pp.93-98

Haynie, F.H., Upham, J.B., (1970), Mater. Prot. Performance 9: 35.

Hills, G.A. (1959), A Ready Reference to the Description of the Land in Ontario and its Productivity, Preliminary Report, Ontario Department of Land and Forests, Toronto.

Henriksen, A., (1980), "Acidification of Freshwaters: a Large Scale Titration", Proc. Intl. Symp., Ecol.Impacts of Acid Precipitation, Norway, SNSF Project. pp.68-74.

Horntvedt, R., Dollard, G.J. and Joranger, E., (Oct. 1980), "Effects of Acid Precipitation on Soil and Forest 2. Atmosphere-Vegetation Interactions", in Ecological Impact of Acid Precipitation, Drablos, D. and Tollan, A. (eds.), pp. 192-1923.

Hough, Stansbury & Associates Limited, (1979), Crown Land Recreation Study: Phase 2 - Future Trends and Management Options, prepared for the Ontario Ministry of Natural Resources.

Hough, Stansbury + Michalski, (1980), Alternative Management Strategies for Lac Seul, Ontario Ministry of Natural Resources, 547 pp.

Hultberg, H. and Wenblad, A., (Oct. 1980), "Acid Groundwater in Southwestern Sweden", in Ecological Impact of Acid Precipitation, Drablos, D. and Tollan, A. (eds.), pp.220-221.

IFPS Users Manual (1980), Execucom Systems Corporation, Release 7.0

Irving, P.M. and J.E. Miller, 1978. "Response of soybeans to acid precipitation alone and in combination with sulphur dioxide", In: Radiological and environmental research division annual report. Ecology. Jan.-Dec., 1978. Argonne National Lab., Argonne, Ill. ANL-67-65, Part III, pp. 17-20.

Irving, P.M. and J.W. Miller, 1977. "Response of soybeans to acid precipitation alone and in combination with sulphur dioxide", In: Radiological and environmental research division annual report. Ecology. Jan.-Dec., 1977. Argonne National Lab., Argonne, Ill. pp. 24-27.

Jacobson, J.S., (Oct. 1980), "The Influence of Rainfall Composition on the Yield and Quality of Agricultural Crops", Ecological Impact of Acid Precipitation, Drablos, D. and Tollan, A. (eds.), pp.41-46.

Jeffries, D.S., Cox, C.M. and Dillon, P.J., (1979), "Depression of pH in Lakes and Streams in Central Ontario During Snowmelt", J. Fish Res. Bd. Can., 36: 640-646.

Jensen, R.W. and Snekvik, E., (1972), "Low pH Levels Wipe Out Salmon and Trout Populations in Southernmost Norway", Ambio. 1: 223-224.

Johnson, M.G., Michalski, M.F.P. and Christie, A.E., (1970), "Effects of Acid Mine Wastes on Phytoplankton Communities of Two Northern Ontario Lakes", J. Fish Res. Bd. Canada, 27: 425-444.

Jonsson, B., (1977), "Soil Acidification by Atmospheric Pollution and Forest Growth", Water, Air and Soil Pollution, 7, 497-501.

Jonsson, B. and Sundberg, R., (1972), "Has the acidification by Atmospheric Pollution Caused a Growth Reduction in Swedish Forests?" Research Note No. 20, Department of Forest Yield Research, Royal College of Forestry, Stockholm, Sweden.

Jordan, M.J. and Lechwater, M.P., (1975) "Effects of Zinc Smelter Emissions in Forest Soil Microflora", Canadian Journal of Microbiology, 21:1855-65.

Kramer J.R., (1976) "Acid Precipitation" in Sulfur in the Environment, part 1, ed. J.D. Nriagu, John Wiley and Sons.

Krupa, S.V., 1981. The effects of dry deposition components of acidic precipitation on vegetation, in Initial Draft of the Proceedings for the Effects of Acid Precipitation on Ecological Systems: Great Lakes Region. Institute of Water Research, Mich. State Univ., East Lansing, Michigan. 17 pp.

Kucera, V., "Effects of Sulphur Dioxide and Acid Precipitation on Metals and Anti-Rust Painted Steel", Ambio, 5, 243 (1976).

Keller, W., (1978), "Limnological Observations on the Aurora Trout Lakes, Ontario Ministry of Environment Publication, Northwestern Region.

Krause, H.H., (1981), Factorial Experiments with Nitrogen, Phosphorous, and Potassium Fertilizers in Spruce and Fir Stands of New Brunswick: 10-Year Results, Canadian Forestry Service, Information Report M-X-123.

Lal Gauri, K., Holdren, G.C., Jr., "Pollutant Effects on Stone Monuments", Environ. Sci. Technol., 15, 386 (1981).

Lang, D.S. and S.V. Krupa, 1978. Injury to vegetation incited by sulphuric acid aerosols and acid rain, 71st Annual Meeting of the Air Pollution Control Association, Houston, Texas.

Lee, G.I. (1979) Factors affecting the transfer of materials between water and sediments. Published as Literature Review No. 1. Eutrophication Information program, Water Res. Centre, University of Wisconsin, Madison, 35 pp.

Lee, J.L., 1981. The effects of acid precipitation on crops, an Initial Draft of the Proceedings of the Effects of Acid Precipitation on Ecological Systems: Great Lakes Region. Institute of Water Research, Mich. State Univ., East Lansing, Michigan. 15 pp.

Lee, J.J., Neely, G.E., and Perrigan, P.C., 1980. Sulphuric acid rain effects on crop yield and foliar injury, Environmental Research Laboratory, U.S. Environmental Protection Agency, Corvallis, Oregon. 21 pp.

Lewin, R.A., (1962), Physiology and Biochemistry of Algae, Academic Press Inc., New York.

Likens G.E., (1976), "Acid Precipitation", Chemical and Engineering News.

Lindberg, J.E., Shriner, D.S. and Hoffman, W.A.Jr., (April 1981), "The Interaction of Wet and Dry Deposition with the Forest Canopy", Proceedings of the Effects of Acid Precipitation on Ecological Systems: Great Lakes Region, Michigan State University.

Linzon, S.N. and Temple, P.J., (Oct. 1980), "Soil Resampling and pH Measurements After an 18-Year Period in Ontario", Ecological Impact on Acid Precipitation, Drablos, D. and Tollan, A., (eds.), pp.176-177.

Liu, B.C., and Yu S.H., (1976), Physical and Economic Damage Functions for Air Pollutants by Receptor, Midwest Research Institute, Report to EPA, No. EPA-600/5-76/011.

Loucks, O.L., (1981), The Concern for Acidic Deposition in the Great Lakes Region, preliminary draft report.

Lundmark, J.E., (1971), "Site Factors and Height Growth of Pine and Spruce in Sweden", (in preparation), Air Pollution across National Boundaries - The Impact on the Environment of Sulfur in Air and Precipitation, Royal Ministry of Foreign Affairs and Royal Ministry of Agriculture, Stockholm, Sweden.

Malmer, N., (1976), "Acid Precipitation: Chemical Changes in Soil", Ambio 5: 231-234.

Mansfeld, F., (January 1980), Regional Air Pollution Study. Effects of Airborne Sulphur Pollutants on Materials, Rockwell International Report to EPA, EPA-600/4-80-007 (NTIS PB81-126351).

Mansfeld, F., Kenkel, J.V., (1977), "Electrochemical Measurements of Time-of-Wetness and Atmospheric Corrosion Rates", Corrosion, 33:13.

McFee, W., (April 1981), "The Action of West and Dry Deposition Components of Acid Precipitation on Litter and Soil", Proceedings for the Effects of Acid Precipitation on Ecological Systems: Great Lakes Region, Michigan State University.

McGovern, P.C. and D. Balsillie, 1973. Sulphur dioxide (1972) - heavy metals (1971) levels and vegetation effects in the Sudbury area, Air Management Branch, Ontario Ministry of the Environment. 50 pp.

McLeod, W., Rogers, R.R., (1969), Corrosion of Metals by Aqueous Solutions of the Atmospheric Pollutant, Sulphurous Acid, Electrochem Technol., 6:231.

Michalski, M.F.P. and N. Conroy, (1973), "The 'Oligotrophication' of Little Otter lake, Parry Sound District", Proc. 16th Conf. Great Lakes, Res. 1973:934-948.

Michalski, M.F.P., Johnson, M.G., and Veal, D.M., (1973), Muskoka Lakes Water Quality Evaluation, Report Number 3, Eutrophication of the Muskoka Lakes, Ontario Ministry of the Environment, Water Resources Branch, Toronto.

Michalski, M.F.P., K.H. Nicholls, and M.G. Johnson (1975), "Phosphorus removal and water quality improvements in Gravenhurst Bay, Ontario", Vech. Internat. Verein. Limnol. 19:644-659.

Minns, C.K., (1980), Acid Rain - "A Preliminary Estimate of the risk of Ontario's Inland Fisheries" - unpublished manuscript.

Morrison, I.K. and Foster, N.W., (June 1979), "Five-Year Growth in Two Nitrogen-Phosphorous Fertilization Experiments in Spruce and Spruce-Fir Upland Forest in Northern Ontario", Canadian Forestry Service Report O-X-299.

Morrison, I.K., Swan, H.S.D., Foster, N.W. and Winston, D.A.. (June 1977), "Ten-Year Growth in Two Fertilization Experiments in a Semimature Jack Pine Stand in Northwestern Ontario", The Forestry Chronicle, 53. No.3.

Morrison, I.K., Winston, D.A. and Foster, N.W., (March 1977), "Effect of Nitrogen, Phosphorous and Potassium Fertilizers on Growth of Semimature Jack Pine Forest, Chapleau Ontario: Fifth-Year Results", Canadian Forestry Service Report O-X-258.

Morrison, I.K., Winston, D.A. and Foster, N.W., (April 1977), Effect of Calcium and Magnesium with and without NPK, on Growth of Semimature Jack Pine Forest, Chapleau, Ontario: Fifth-Year Results, Canadian Forestry Service Report O-X-259.

Morrison, I.K., Winston, D.A. and Foster, N.W., (July 1977), Effect on Nitrogen Fertlization and Low Thinning on Growth of Semimature Jack Pine Forest, Chapeau, Ontario: Fifth-Year Results, Canadian Forest Service, Report O-X-267

Morrison, I.K., (1974), Mineral Nutrition of Conifers With Special Reference to Nutrient Status Interpretation: a Review of Literature, Can. For. Serv. Publ. 1343.

Mulvaney, J.N. and Hadden, D.W., (1981), A Submission to the United States Environmental Protection Agency Opposing Relaxation of SO_2 Emission Levels in State Implementation Plans and Urging Enforcement, Ontario Ministry of Environment Publication.

Murray, A.R., (July 1981), "Acid Rain: Nature, Scope and Prognosis", Paper presented at the 1981 Canadian Sport Fisheries Conference.

Nriagu, J.O., Ed., (1978), "Sulphur in the Environment", Vol. II., Ecological Impacts, John Wiley and Sons.

Nyberg M., (1978), "Sulphur Pollution and Soil", in Sulphur in the Environment, Part 11, ed. Nriagu, J.O., John Wiley and Sons.

OECD (Organization for European Cooperation and Development), (1979), Env/Air/7.9.12 pp.247.

Ontario Ministry of Agriculture and Food, (June 1981), Agricultural Statistics for Ontario 1980.

Ontario Ministry of Agriculture and Food, (1980a) Agricultural Statistics for Ontario 1979. Economics Branch, Publication 20. 54 pp.

Ontario Ministry of Agriculture and Food, (1980b), Fruit and vegetable production in Ontario, 1979, (Annual Summary), Economics Branch. 12 pp.

Ontario Ministry of Agriculture and Food, (Dec. 1979), Agricultural Statistics for Ontario 1941-1978.

Ontario Ministry of the Environment, (October 1980), The Case Against the Rain, Ontario.

Ontario Ministry of the Environment, (July 15, 1980), Background Paper on Proposed Socio-Economic Studies of Acid Precipitation.

Ontario Ministry of the Environment, (1979), A Statement to the Standing Committee on Resource Development on Acidic Precipitation in Ontario.

Ontario Ministry of the Environment, (1978), Limological Observations on the Aurora Trout Lakes.

Ontario Ministry of Natural Resources, (April 1972), Forest production Policy Options for Ontario, Ontario.

Ontario Ministry of Natural Resources, (1980), Statistics 1980.

Ontario Ministry of Treasury and Economics, (1980), Ontario Statistics 1980.

Overrein, L.N., Seip, H.M., and Tollan, A., (1980), Acid Precipitation-Effects on Forest and Fish Final Report of the SNSF-Project 1972-1980, Oslo, Norway.

Pentland, R.L., (1968), "Runoff characteristics in the Great Lakes Basin", Proc. 11th Conf. Great Lakes Res. Ont. Assoc. Great Lakes Res., 326-359.

Plonski, W.L., (1974), Normal Yield Tables (Metric) for Major Forest Species of Ontario, Ontario Ministry of Natural Resources.

Rennie, P.J. and Halstead R.L., (1977), "The Effects of Sulphur on Plants in Canada", Sulphur and its Inorganic Derivatives in the Canadian Environment, National Research Council, Ottawa.

Rennie, P.J., "Forest Fertilization Research in Canada".

Reuss, J.O., (1980), "Chemical and Biological Relationships Relevant to the Effect of Acid Rainfall on the Soil-Plant System", Water Air Soil Poll., 7: 461-478.

Ryan, P.M. (1976), "Changes in the growth and members of rock bass Amblophlites rupestris (Rafinesque) and yellow perch Perca flavescens (Mitchell), in the La Cloche Mountain Lakes as a result of acid precipitation", M.Sc. Thesis, Univ. of Toronto, 416 pp.

Ryder, R.A., (1979), "Assessing the Potential Fish Yield of Infertile Lakes - A Management Prognosis", Paper Presented at 1979 North American Lake Management Conference, Michigan State University, E. Lansing.

Ryder, R.A., Kerr, S.R., Loftus, D.H. and Regier, H.A., (1974), "The Morphoedaphic Index, a Fish Yield Estimator - Review and Evaluation", J. Fish. Res. Board Can., 31: 663-688.

Ryder, R.A. (1965), "A Method of Estimating the Potential Fish Production of North Temperate Lakes", Trans. Amer. Fish. Soc., 94: 214-218.

Ryder, R.A. (1980) "The Costs of Internal Corrosion in Water Systems", Journal of the American Water Works Association.

Riederer, J., "Pollution Damage to Works of Art", in "New Concepts in Air Pollution Research", J. Wilhems, Ed., Birkhauser-Verlag, 1974, pp. 73 - 85.

Salmon, R.L., (1970), Systems Analysis of the Effects of Air Pollution on Materials, Midwest Research Institute Report to National Air Pollution Control Administration, NTIS PB 209-192.

Schindler, D.W., Armstrong, F.A.J., Holmgren, S.K. and Brunskill, G.J., (1971), "Entrophication of Lake 227, Experimental Lakes Area, Northwestern Ontario, by the Addition of Phosphate and Nitrate", J. Fish. Res. Board Can., 28: 1763-1782.

Schindler, D.W. and S.K. Holmgnen (1971), "Primary production and plytoplankton in the Experimental Lakes Area, northwestern Ontario and other low carbonate waters, and a liquid scintillation method for determining 4C activity in photosynthesis", J. Fish. Res. Brd. Can. 28:189-201.

Schindler, D.W., Kling, A., Schmidt, R.V., Prokopowich, J., Frost, V.E., Reed, R.A. and Chapel, M., (1973), "Eutrophication of Lake 227 by addition of phosphate and nitrate: the second, third and fourth years of enrichment, 1970, 1971 and 1972", J. Fish. Res. Brd. Can. 30:1415-1440.

Schindler, D.W., Kalff, J., Welch, H.E., Brunskill, G.J., Kling, H. and Krutsch, N., (1974), "Eutrophication in the high arctic - Meretta lake, Cornwalles Island (75^{O}N lat.), J.Fish. Res. Brd. Can. 31:647-662.

Schlesinger, D.A. and Regier, H.A., (1982) "Climatic and morphoedaphic indices of fish yields from natural lakes", Trans. Am. Fish. Soc. (in press).

Schneider, J.C., (1975), "Typology and Fisheries Potential of Michigan Lakes", The Michigan Academician, 8: 59-84.

Sengupta, M., DeGast, A.A., Can. Mining Metals, Bull. 65:54, (1972).

Sereda, P.J., "Effects of Sulphur on Building Materials", in Sulphur and It's Inorganic Derivatives in the Canadian Environment, National Research Council of Canada, Pub. No. NRCC 15015, 1977, pp. 359 - 426.

Shaffer and Associates, (1981), A Study of the Economic Losses Due to Acid Rain as Indicated by the Cost of Increased Atmospheric Corrosion, Report to Environment Canada.

Shriner, D.S., (1978), "Effects of Simulated Acidic Rain on Host-Parasite Interactions in Plant Diseases", Phytopathology, 68: 213-218.

Shriner, D.S., (1978), Interactions between acidic precipitation and SO_2 or SO_3: Effects on plant response, Phytopathol News. 12: 153.

Spence, J.W., Haynie, F., Upham, J.B., (1975), "Effects of Gaseous Pollutants on Paints: A Chamber Study", J. Paint, Technol., 47:57.

Stankunas, Unites, McCarthy, (June 1981),Air Pollution Damage to Man-made Materials, Report prepared for the Electric Power Institute.

Strand, L., (Oct. 1980), "The Effect of Acid Precipitation on Tree Growth", Ecological Impact of Acid Precipitation, Drablos, D. and Tollan, A., (eds.), pp. 64-67.

Stuanes, A., (1980), "Effects of Acid Precipitation on Soil and Forest - 5. Release and Loss of Nutrients from a Norwegian Forest Soil Due to Artificial Rain of Varying Acidity", Ecological Impact of Acid Precipitation, Drablos, D. and Tollan, A., (eds.), pp.198-199.

Tamm, C.O. and Cowling, E.B., (1977), "Acidic Precipitation and Forest Vegetation", Water Air Soil Poll., 7: 503-511.

Tamm, C.O. and Wiklander, G., (1980), "Effects on Artificial Acidification with Sulphuric Acid on the Growth in Scots Pine Foret", Drablos, O. and Tollan, A., (eds.), Ecological Impact of Acid Precipitation, p. 188-189, SNSF-project.

Tomlinson, G.H., (February 1981), Acid Rain and the Forest - the Effect of Aluminum and the German Experience, Research Centre, Senneville, Quebec.

Troedsson, T., (Oct. 1980), "Ten Years Acidification of Swedish Forest Soils", Ecological Impact of Acid Precipitation, Drablos, D. and Tollan, A., (eds.), p.184.

Tveite, B., (Oct. 1980), "Effects of Acid Precipitation on Soil and Forest - 8. Foliar Nutrient Concentrations in Field Experiments", Ecological Impact of Acid Precipitation, Drablos, D. and Tollan, A., (eds.), p.204-205.

Tveite, B., (Oct. 1980), "Effects of Acid Precipitation on Soil and Forest - 9. Tree Growth in Field Experiments", Ecological Impact of Acid Precipitation, Drablos, D. and Tollan, A., (eds.), pp.206-207.

Tveite, B. and Abrahamsen, G., (1980), "Effects of Artificial Acid Rain on the Growth and Nutrient Status of Trees", Effects of Acid Precipitation on Terrestrial Ecosystems, Hutchinson, T.C. and Havas, M., (eds.), pp.305-318.

Tveite, B., 1980a. "Effects of acid precipitation on soil and forest: tree growth in field experiments", in Drablos, D. and A. Tollan (eds.) Ecological Impacts of Acidic Precipitation. Proc. Intl. Conf., Norway, 1980. pp. 206-207.

Tveite, B., 1980b. "Effects of acid precipitation on soil and forest: the effects on growth of Norway Spruce of soil acidity by acid irrigation", in Drablos, D. and A. Tollan (eds.) Ecological Impacts of Acidic Precipitation. Proc. Intl. Conf. Norway, 1980. pp. 208-209.

Ulrich, B., (1978), "A Systems Approach to the Role of Nutrients in Controlling Rehabilitation of Terrestrial Ecosystems", in Breakdown and Restoration of Ecosystems, pp.105-121, NATO Conference Series 3.

Ulrich, B., Mayer, R. and Khama, P.K., (1980), "Chemical Changes Due to Acid Precipitation in a Loss Revived Soil in Central Europe", Soil Science, 130, 193-199.

United States - Canada Memorandum of Intent on Transboundary Air Pollution, Interim Report of Work Group I (Impact Assessment), February 1981.

Wang, K.T. and Chin, V.I., (1978), "Ground Water Resources; Northern Ontario Water Resources Studies", Ontario Ministry of the Environment Water Resources Report 11G, 87 pp + app.

Weaver, M., Heritage Canada, personal communication, June 1981.

Wiklander, L., (1980), "Interaction Between Cations and Anions Influencing Absorption and Leaching", Effects of Acid Precipitation on Terrestrial Ecosystems, Hutchinson, T.C. and Havas, M., (eds.), pp.239-254.

Winston, D.A., (February 1977), Fertilization and Strip Thinning in 45 Year-Old Jack Pine in Ontario, Canadian Forestry Service, Report O-X-256.

Winston, D.A., Morrison, I.K. and Foster, N.W., (July 1977), Nitrogen and Herbicide Treatments in Semimature Jack Pine Forest, Chapleau, Ontario: Fifth-year Results, Canadian Forestry Service, Report O-X-266.

Wood, T. and Borman, F.H., (1974), "The Effects of an Artificial Acid Mist Upon the Growth of Betula Alleghaniensis", Brit. Environ. Pollut., 7: 259-268.

Yocom, J.E., Grappone, M., "Effects of Power Plant Emissions on Materials", TRC Inc. Report to Electric Power Research Institute, Palo Alto, Ca., July 1976.

Yocom, J.E., Upham, J.B., "Effects on Economic Materials and Structures", in "Air Pollution", 3rd Edition, Vol. II, A.C. Stern, Ed., Academic Press, 1977, pp. 65 - 158.